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Grupo de Física Nuclear Experimental

Beta-delayed Charged particles : Peering into Nuclear Structure

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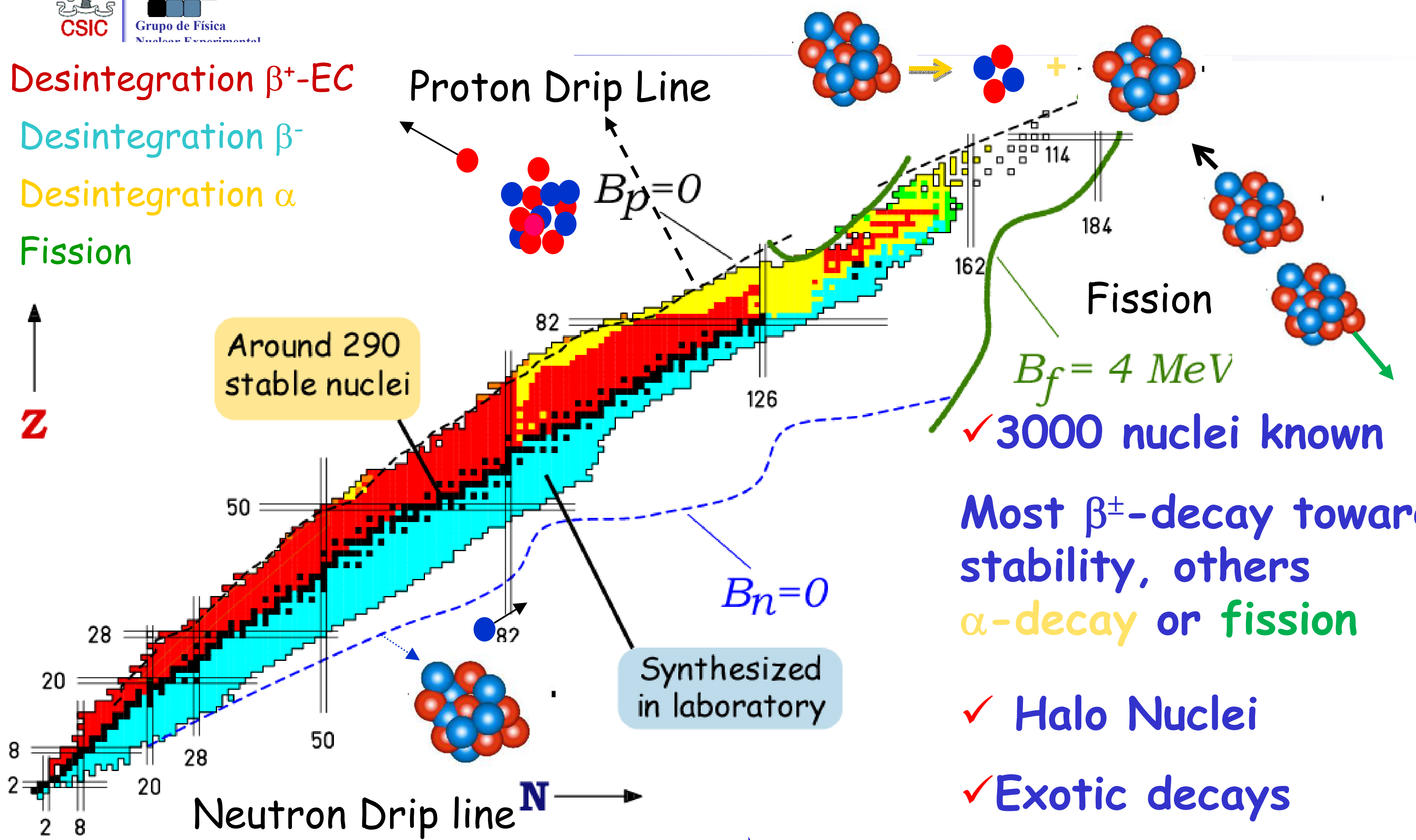
Nuclear Landscape



✓3000 nuclei known

Most β±-decay towards stability, others α-decay or fission

✓ Halo Nuclei

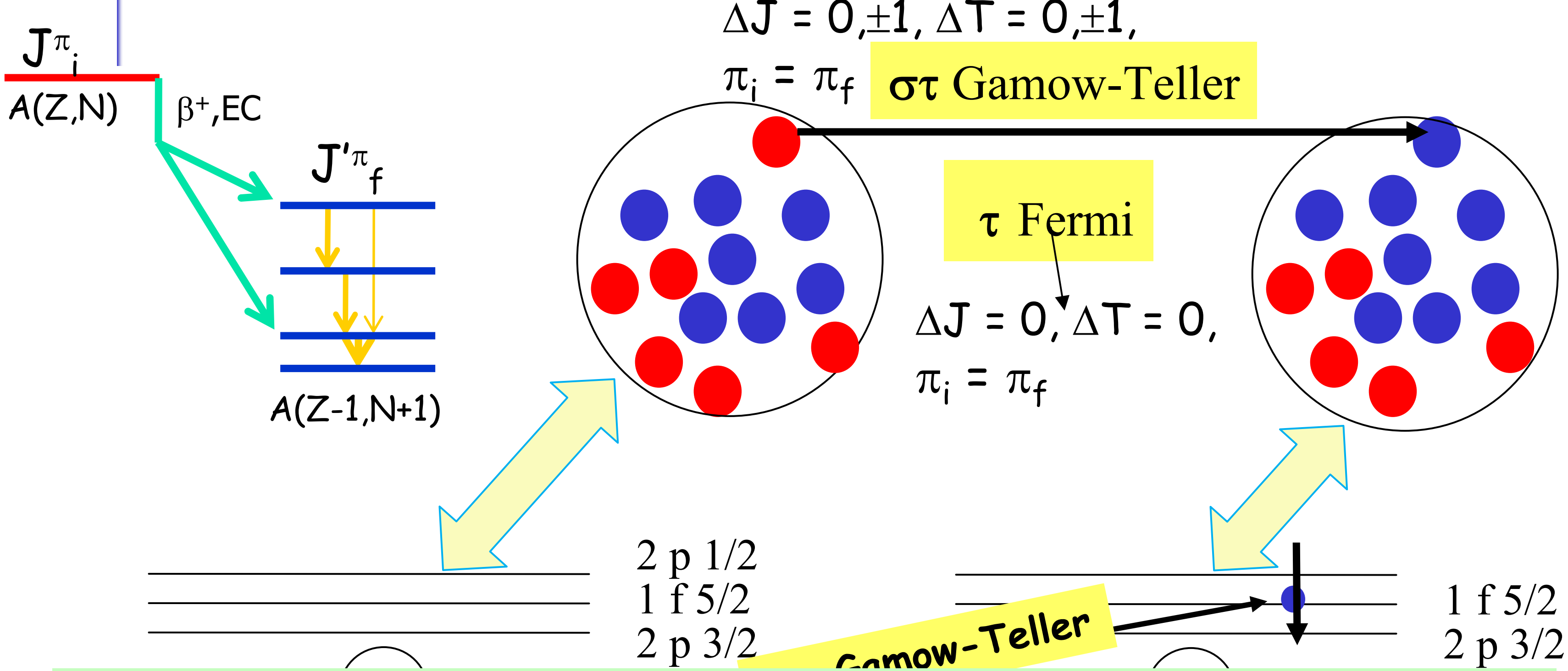
✓Exotic decays

✓Asymmetries

✓Order to Chaos

Near the drip lines

β-decay process

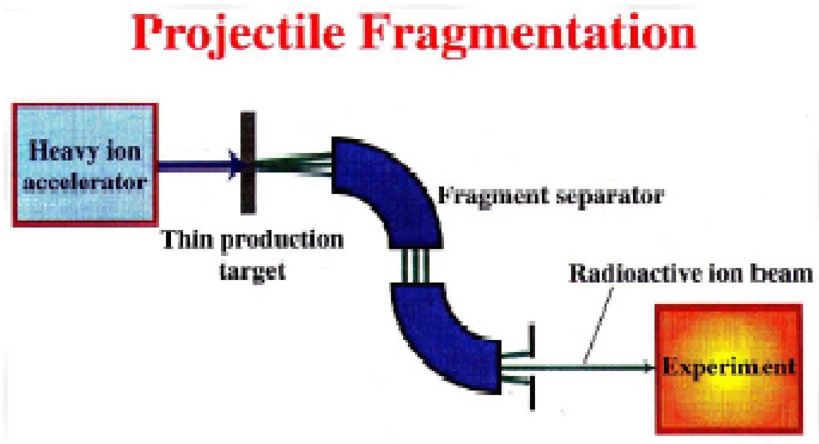


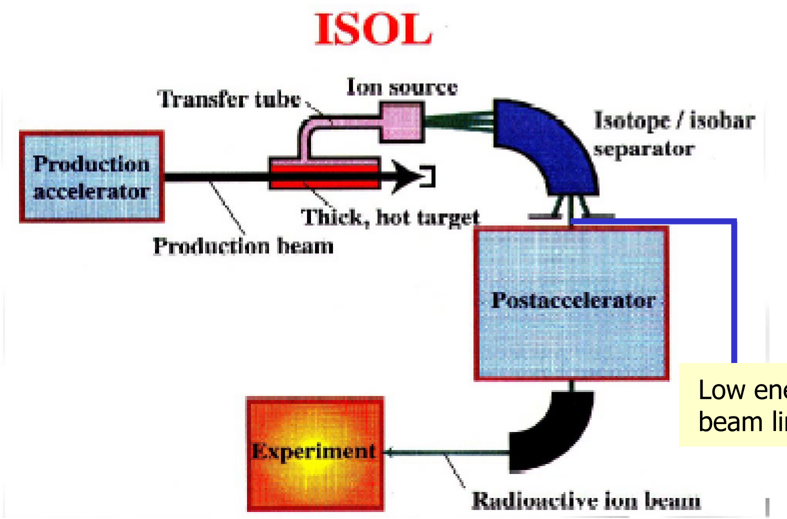
- $\beta^{\pm}$-decay gives first glance on the structure by the half-life
- Detailed spectroscopy gives the microscopic structure

$$B_{GT} = \left| \langle \psi_f \mid \sum \sigma\tau^{\pm} \mid \psi_i \rangle \right|^2$$

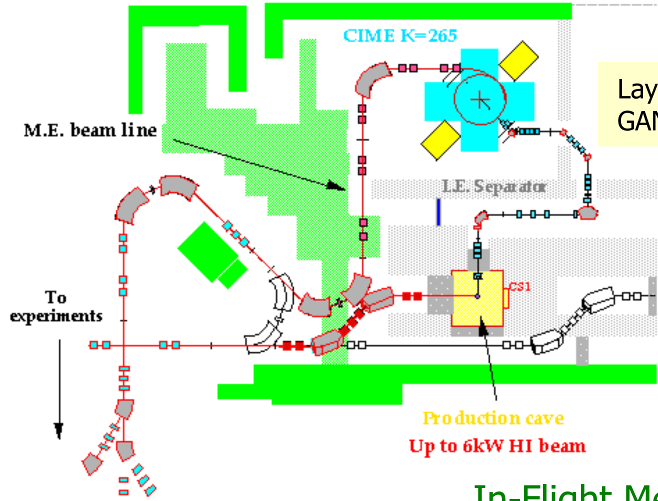
$$B_F = \left| \langle \psi_f \mid \sum \tau^{\pm} \mid \psi_i \rangle \right|^2$$

Production of Exotic Nuclei

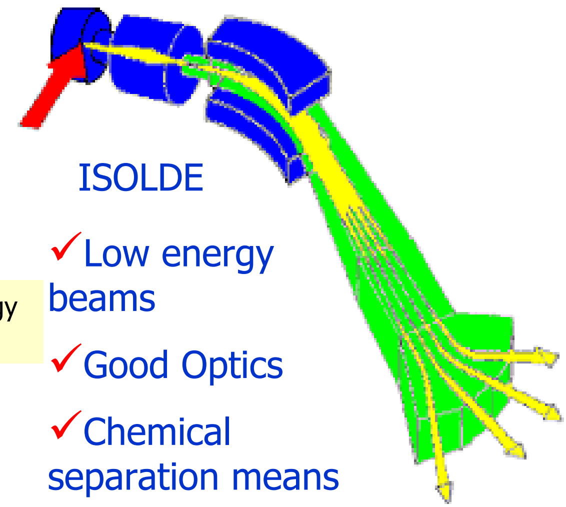




Low energy beam line



Layout of GANIL



ISOLDE

- ✓Low energy beams
- ✓Good Optics
- ✓Chemical separation means

In-Flight Method

- ✓Short separation times
- ✓Direct determination of B.R.
- ✓High efficiency due to deep implantation on detectors
- ✓Simultaneous Measurement of several nuclei

Decay properties of exotic nuclei

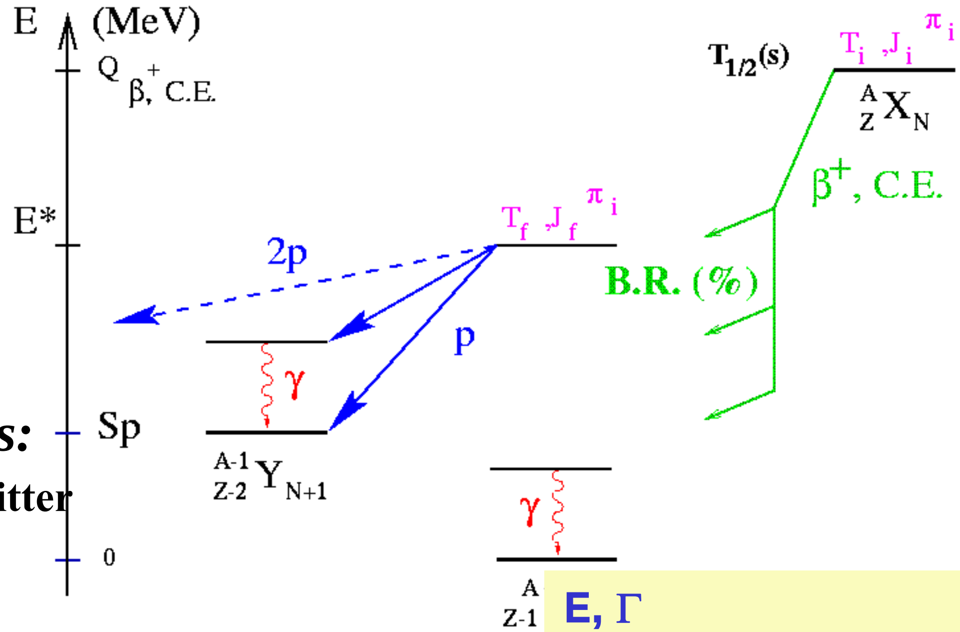
1916 **Rutherford & Wood** βα [*Philos. Mag.* ***31*** *(1916) 379*]

1963 **Barton & Bell** identified ^{25}Si as **βp**

➢ Global properties

- ***Short half-lives (~ms)***
- ***High Q_β values***
- ***Low $S_{p/n}$ values***

→ β-delayed particle emission



➢ β⁺ (C.E.) emission

- ***β-delayed particle spectrum depends:***
  - **beta-feeding to the unbound levels in emitter**
  - **Probability to emit the charged particle**
- ***Reduced transition probability:***

$$ft = f * \frac{T_{1/2}}{B.R.} = \frac{K}{G_V^2|\tau|^2 + G_A^2|\sigma\tau|^2} = \frac{C}{B(F) + B(GT)}$$

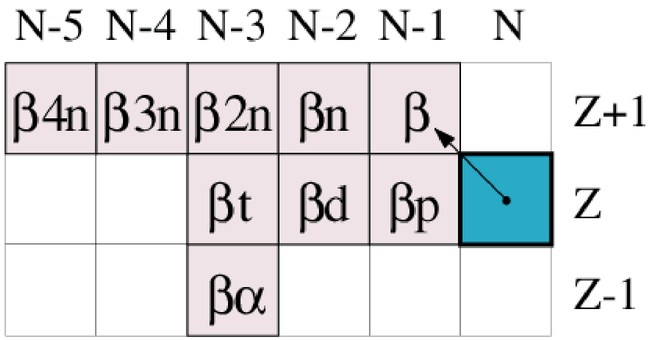
E, Γ

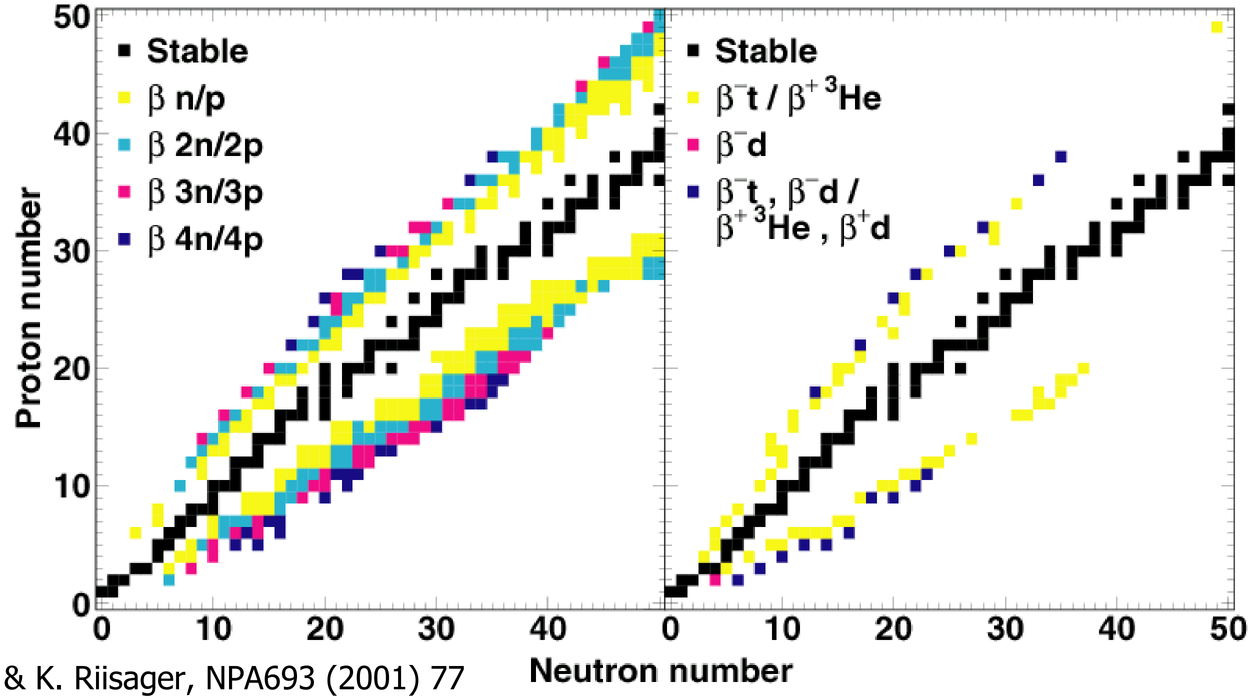
Level density

Spin, Isospin

β-decay properties

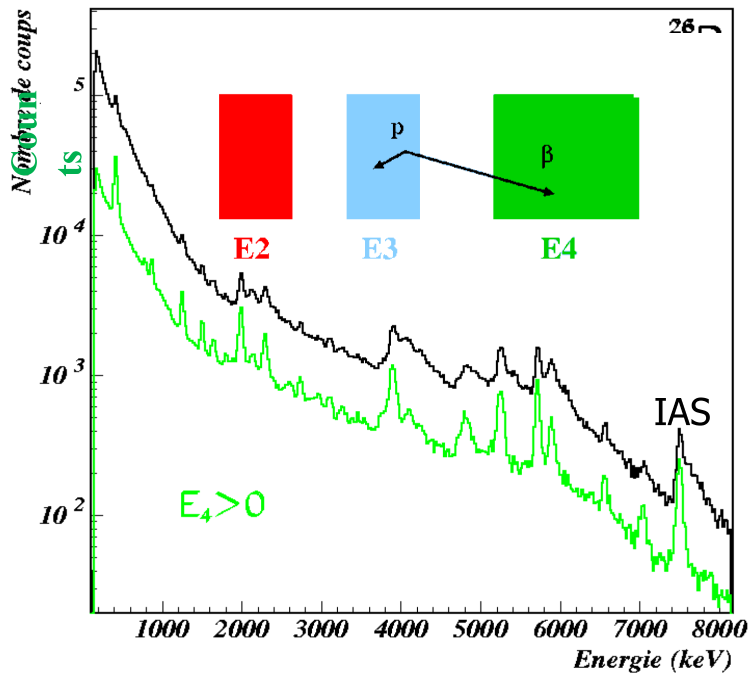
Beta delayed particle emitters

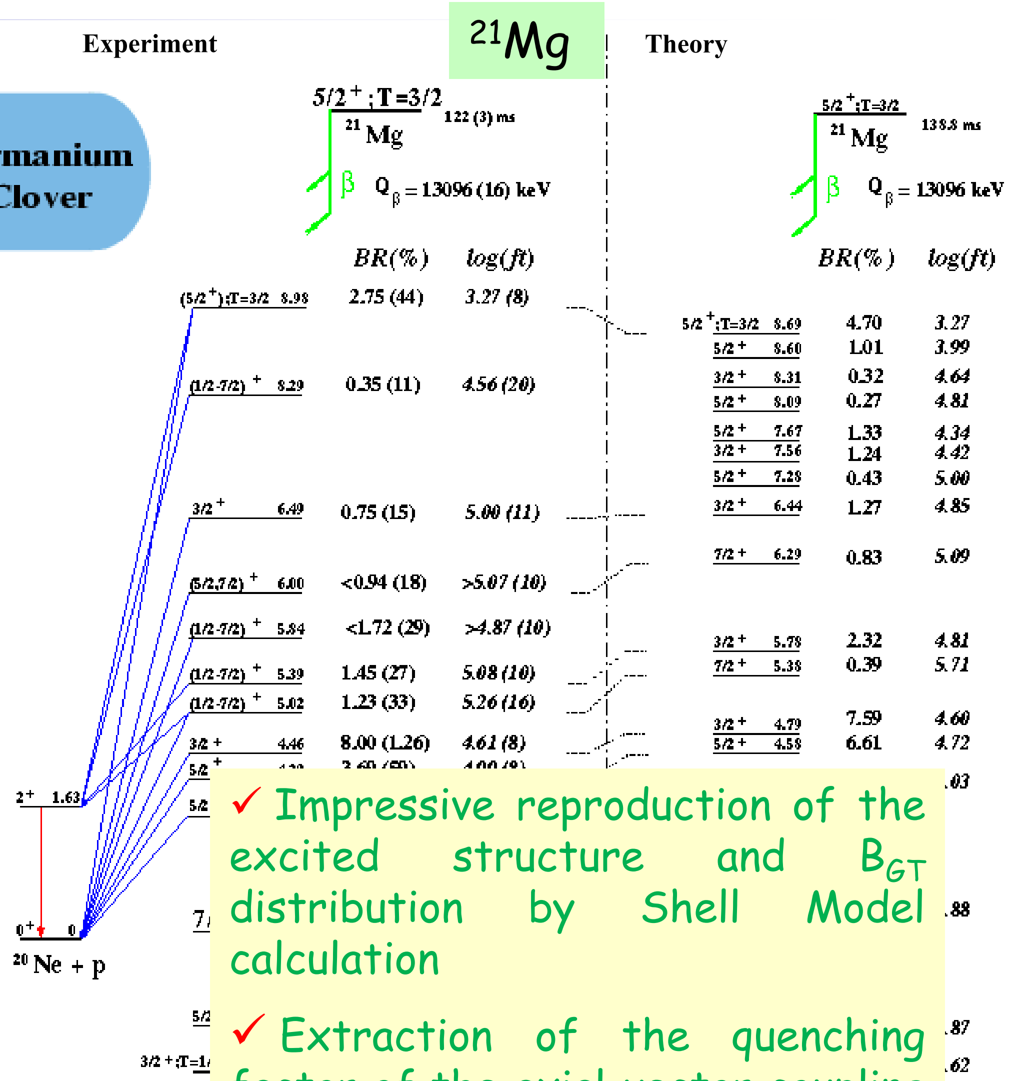




B.Jonson & K. Riisager, NPA693 (2001) 77

Powerful Source of Nuclear Structure Information





β-delayed proton spectrum gives level information in a broad energy range

✓ Impressive reproduction of the excited structure and B_{GT} distribution by Shell Model calculation

✓ Extraction of the quenching factor of the axial-vector coupling constant

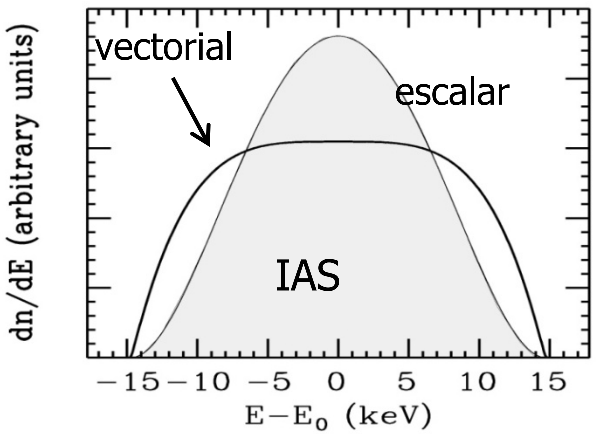
Search for New Physics

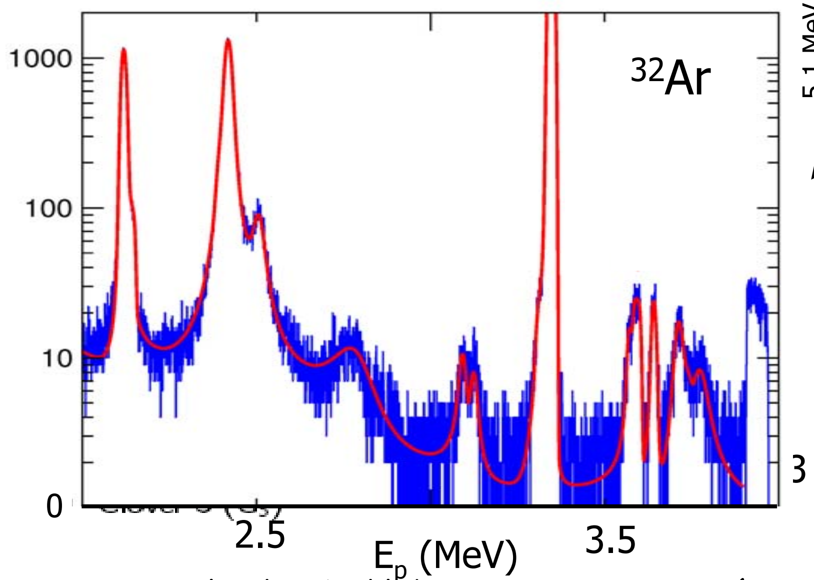
✓e-ν correlation a good probe of weak interactions

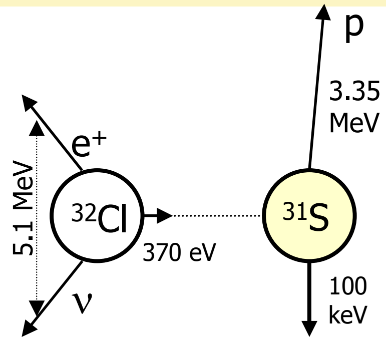
✓ The V-A character of β-decay determined by measuring e-ν correlation through the daughter recoil in 1963

✓Improved precision to find new physics by using βp emitter . e-ν correlation determined from the broadening of proton peak from IAS in $0^+ \rightarrow 0^+$ transitions

✓Supersymmetry and Models with lepto-quarks predicts scalar contributions to the weak interactions.







- Isospin mixing in Fermi decays
- Limit for scalar component in beta decays $|C_A/C_V|^2 < 3.6\times10^{-3}$

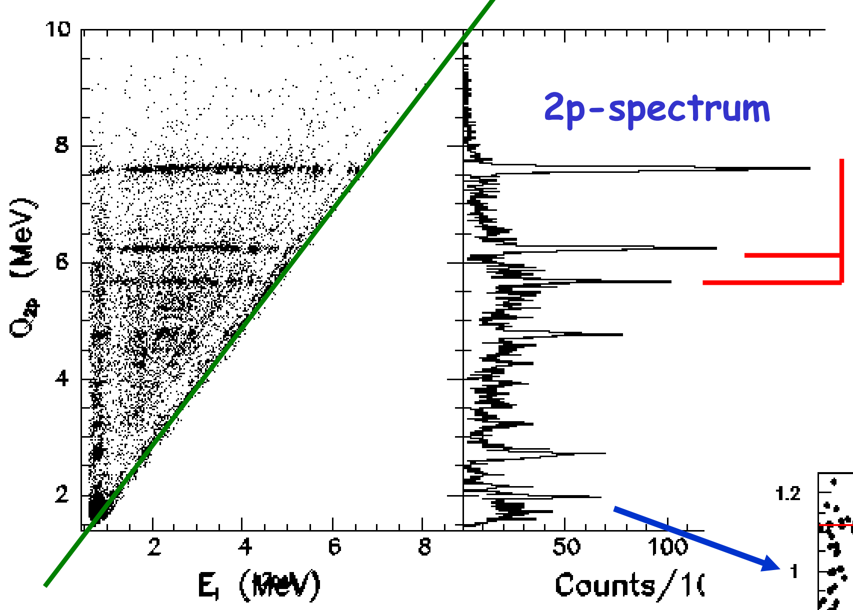
- Absolute branching ratios /MSU
- Very precise $T_{1/2}$ determination /ISOLDE
- ft = 1552(12) s for the Fermi decay
- Isospin Symmetry breaking Correction

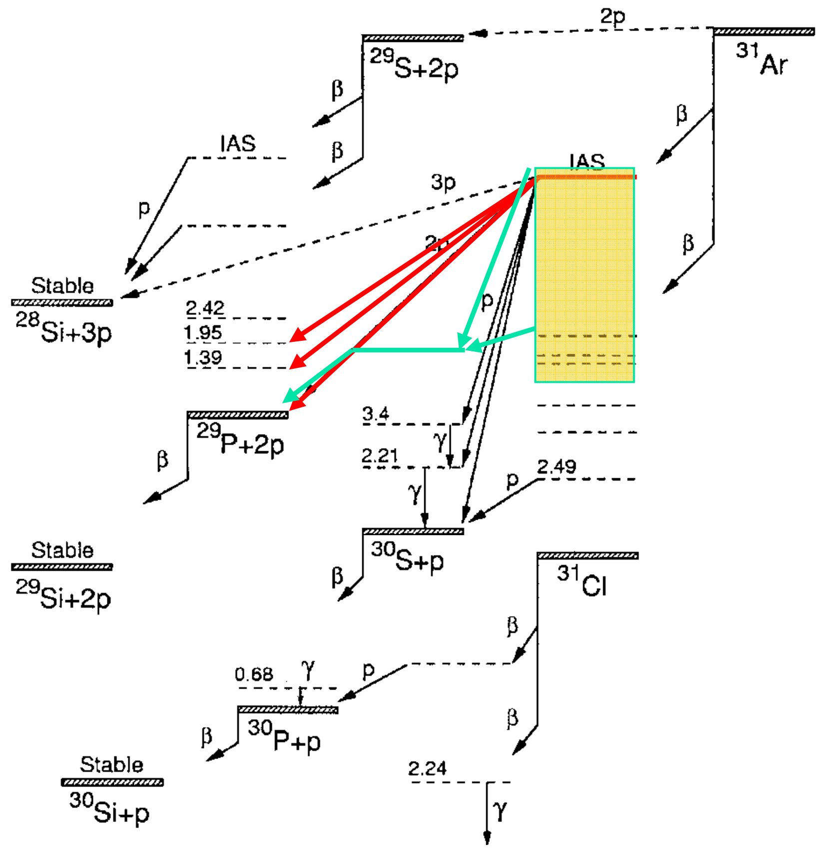
  δ_c = 2.0(4) %

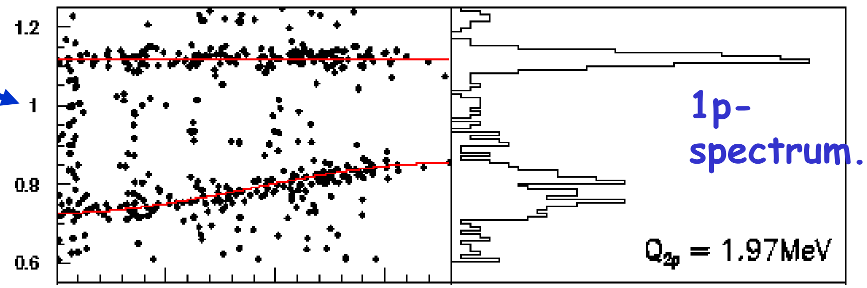
^{31}Ar β-2p emitter

Decay of IAS through
2p emission

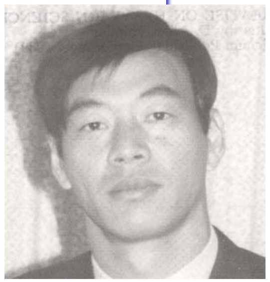
Diagonal from decays via single intermediate state from many initial states fed in beta-decay





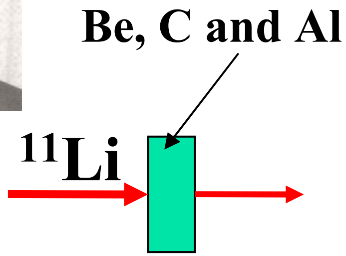


Surprise at the neutron drip line: Halo nuclei

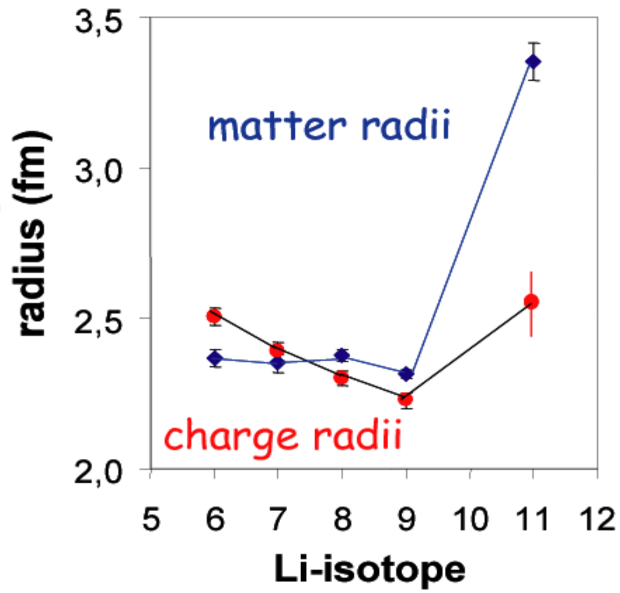


Tanihata

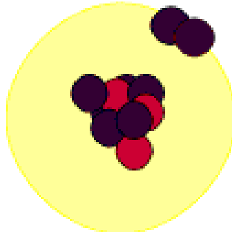
1985, First experiments with radioactive nuclear beams, Berkeley (USA)



$$\sigma_I \Rightarrow \left\langle r^2_{mass} \right\rangle^{1/2}$$



$$\sigma_I(p,t) = \pi[R_I(p) + R_I(t)]^2$$



Hansen & Jonson

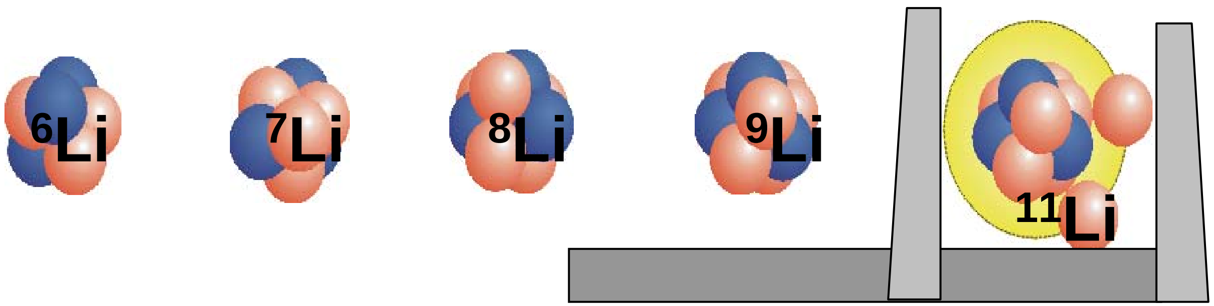
Europhys. Lett. 4 (1987) 287

$R_m(^{11}Li) = 3.30(24)$ fm

$R_c(^{11}Li) = 2.47(4)$ fm

¿Why is the mass radius so large?

- ✓Energy threshold effect (S_{2n} = 378(5)keV)
- ✓Highlight by nuclear reactions
- ✓Effects in beta decay



Beta decay of an exotic nuclei

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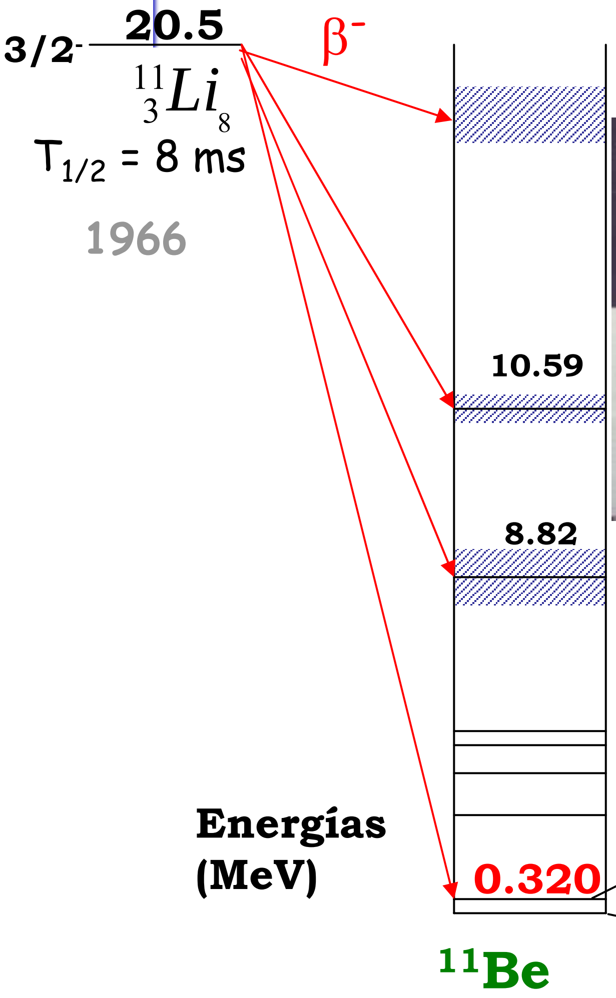
Even a neutron rich - nuclei emit charged particles



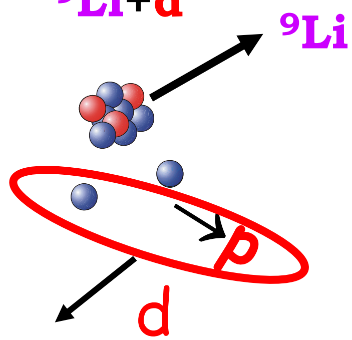
1974
0.504
^{10}Be+n

1979
7.315
^{9}Be+2n

1980
8.982
2α+3n

1983
15.721
^{8}Li+t

1996
17.916
^{9}Li+d

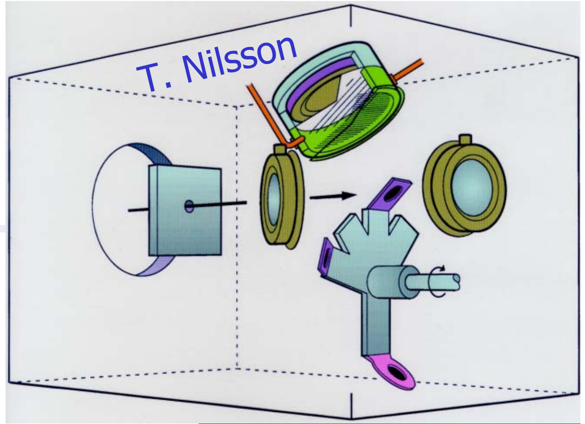


0.320 ½-
γ
½+
^{11}Be

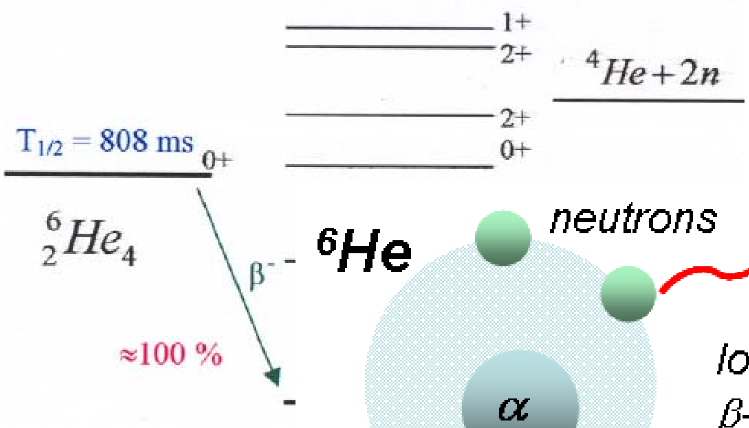
Q = 20.54 MeV,
$T_{1/2}$= 8.2 ms
b(320) = 6.3(6) %

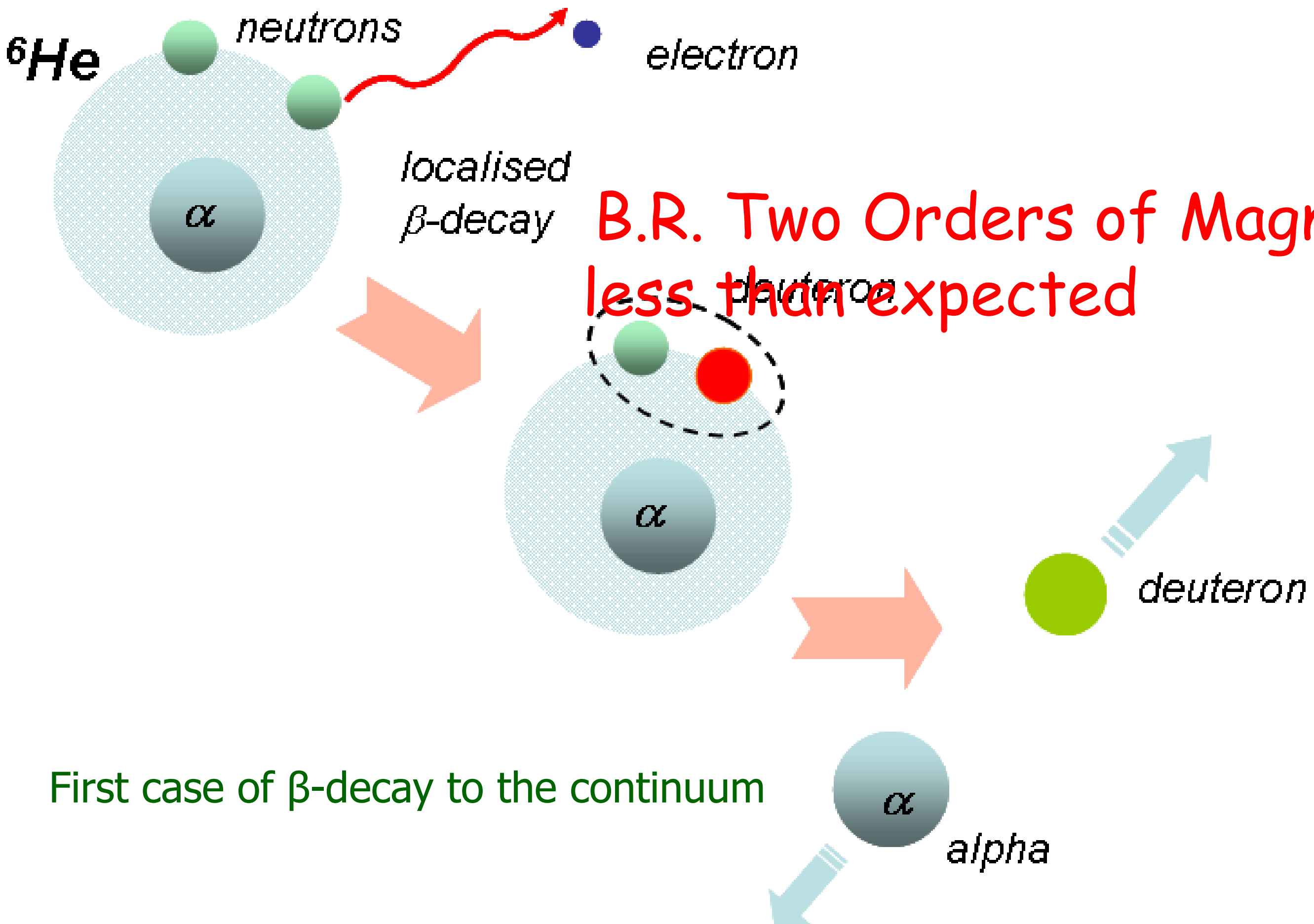
$(1s_{1/2})^2/(0p_{1/2})^2 \sim 1$

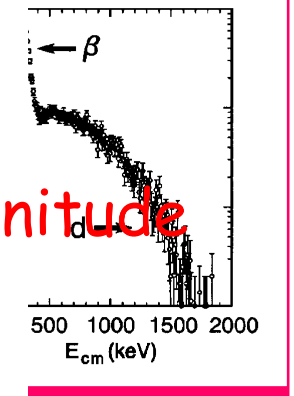
Beta-delayed deuterons



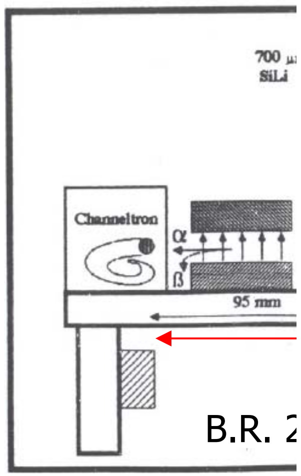
$Q_{\beta d}$ = 3.007 – S_{2n} MeV





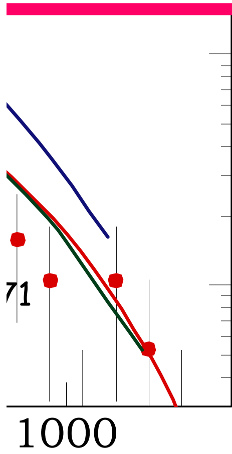


B.R. Two Orders of Magnitude less than expected



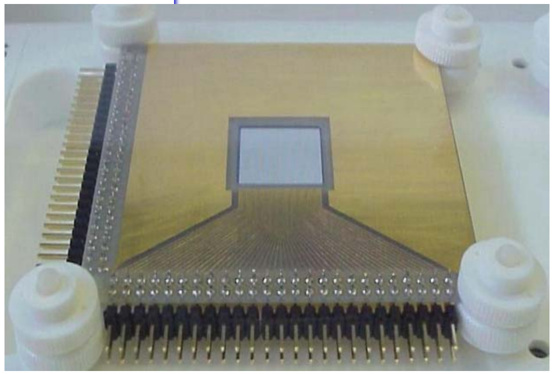
B.R. 2

Riisager et al., I



First case of β-decay to the continuum

^{11}Li βd spectrum finally measured @ TRIUMF!!

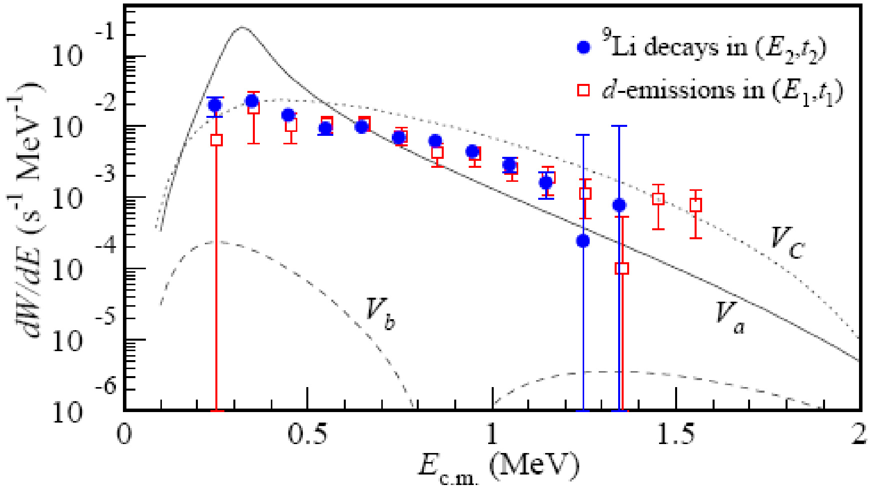


DSSSD 16x16 mm^2, 70μm thick

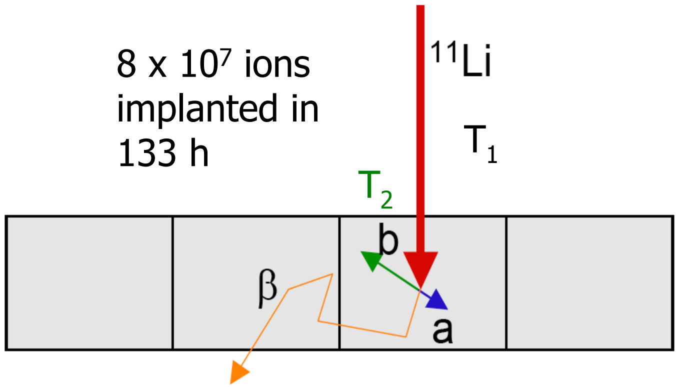
48x48 strips, 300 μm, 2304 pixels

J. Büscher et al., NIM B in press

- Implantation of 11Li beam on DSSSD Detector
- Very precise B.R.
- Low detection threshold
- Low beta background
- History of each decay



8 x 10^7 ions implanted in 133 h



B.R = 1.30(13)x10-4

E_{cm} > 200 keV

Deuteron Spectrum

Decay to the continuum confirmed

Raabe et al, PRL 101 (2008) 212501

Exotic Radioactivities

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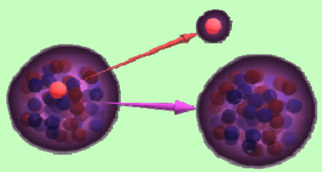
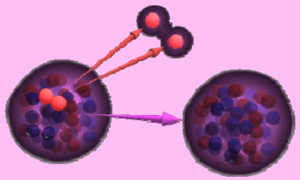
1p-radioactivity

(Z,N) → p + (Z-1,N)

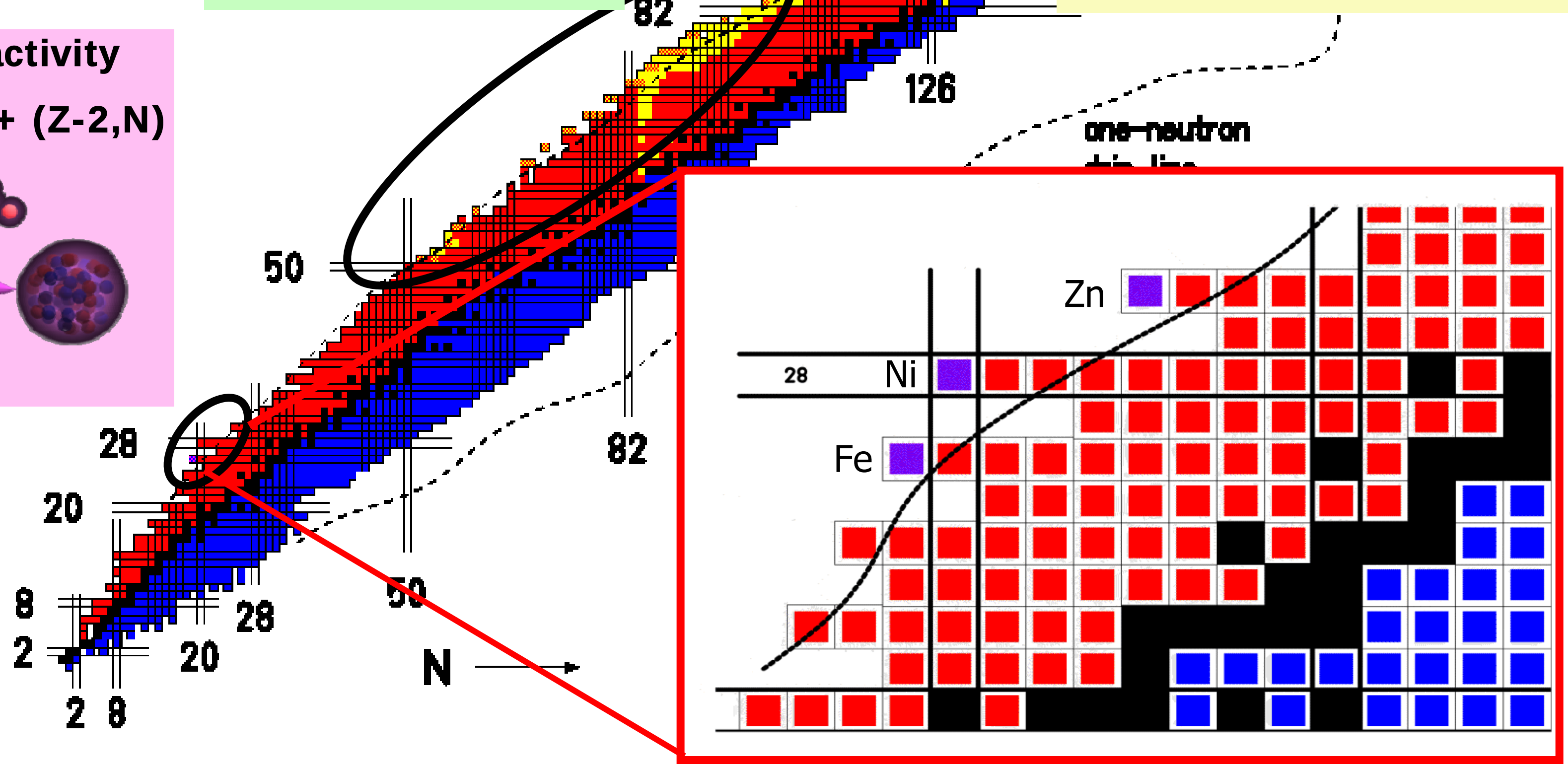


2p-radioactivity

(Z,N) → 2p + (Z-2,N)



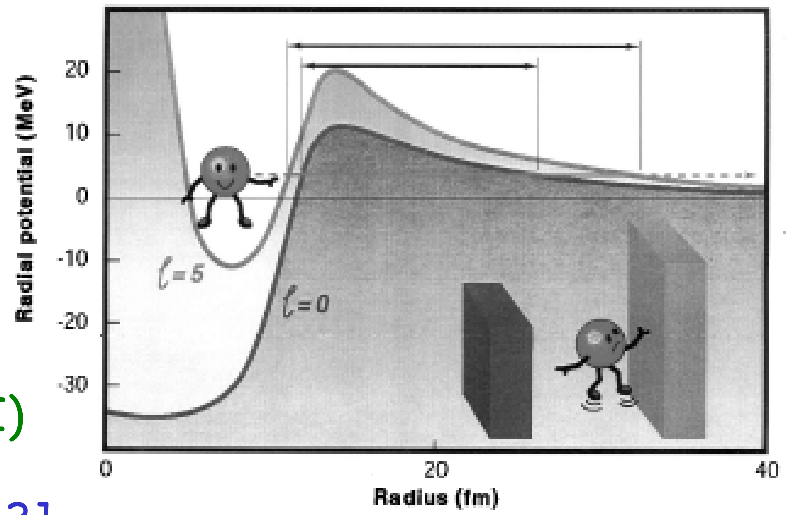
These nuclei at the edge of nuclear existence highlight various phenomena related to the binding of nucleons in the nucleus



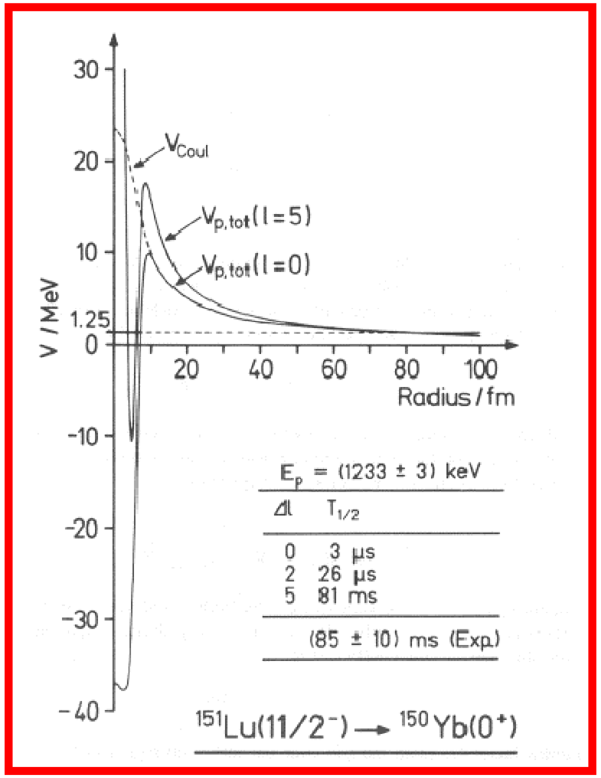
1 Proton Radioactivity

✓ Proton-radioactivity from gs fixed the proton drip-line of this region.

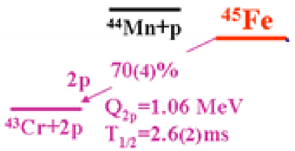
✓ First observed in ^{151}Lu & ^{147}Tm (1981 @ GSI)



- Emission of protons only from odd-Z ∈[50-83], 28 g.s. proton emitters identified.
- The sensitivity of $T_{1/2}$ to angular momentum allows for the assignment of the orbital from which the proton is emitted.
- As protons are detected with high efficiency, proton emitters are used to identify nuclei in Recoil Decay Tagging (RDT).
- p-emission from *highly deformed* nuclei has been observed and decay rates explained assuming Nilsson states.
- Stringent test of shell model beyond drip line.



Two proton Radiactivity



Found 2002

By Bordeaux & Warsaw

Predicted in the 60's by Goldanskii as consecuence of the pairing force ⇒ easier to eject the pair that break it apart

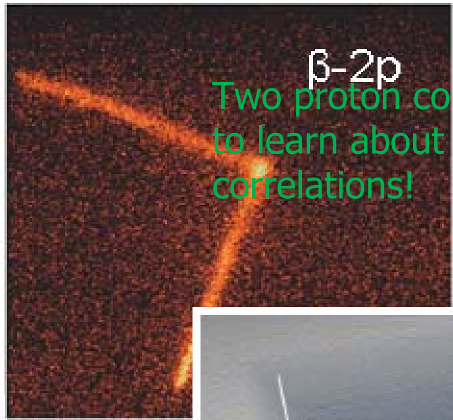
Miernik et al,

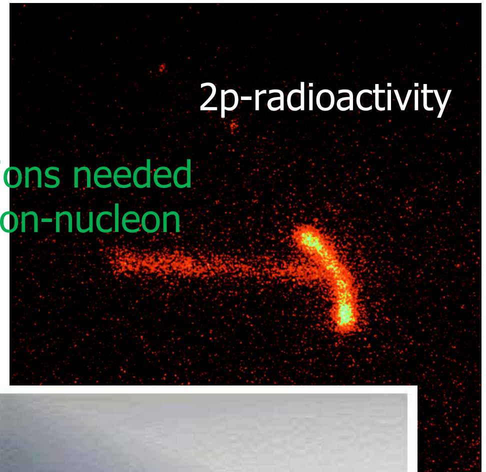
NIM A 581 (2007) 194

PRL 99 (2007) 192501

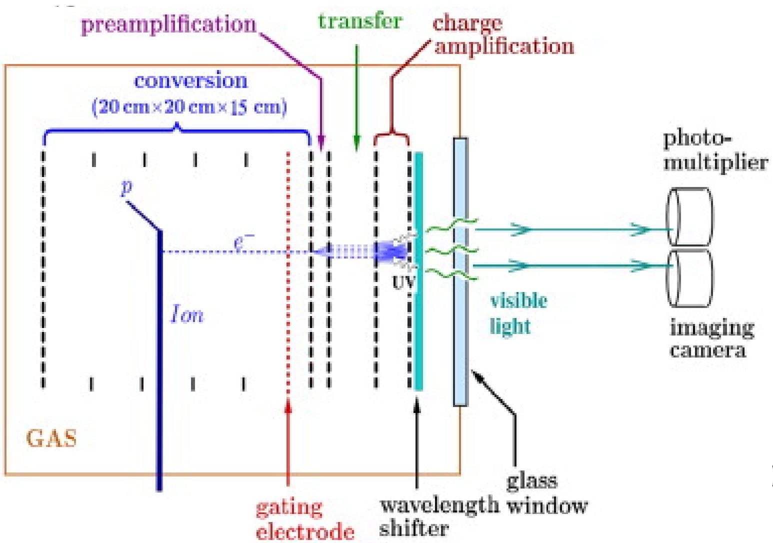
PRC 76 (2007) 041304R

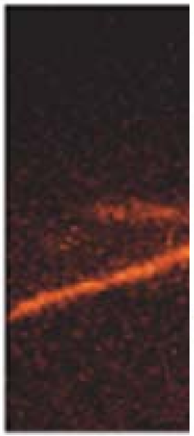
2p-correlations observed in 2007

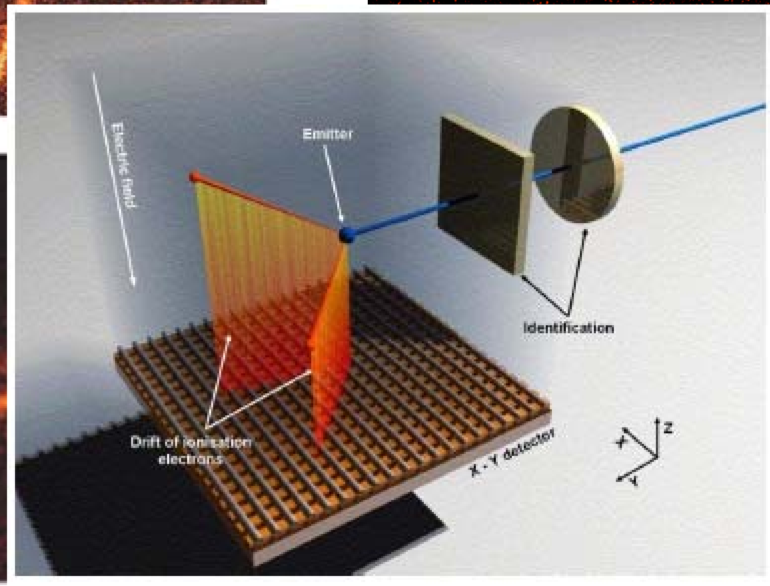


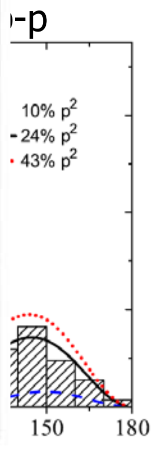


Two proton correlations needed to learn about nucleon-nucleon correlations!









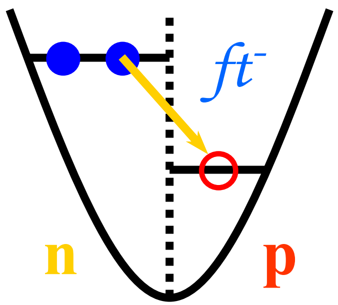
Mirror Asymmetry ?

- Charge independence hypothesis of nuclear interactions: symmetry of analog β transitions

$\beta^+ \; : p \rightarrow n + e^+ + \nu$

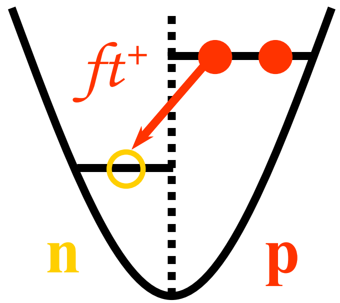
E.C. : $p + e^- \rightarrow n + \nu$

$\beta^- : n \rightarrow p + e^- + \bar{\nu}$



$$ft^{\pm} = \frac{K}{g_V^2 B_F^{\pm} + g_A^2 B_{GT}^{\pm}}$$

$$K/g_V^2 = 6146(6)s \quad g_A^2/g_V^2 = 1.587(3)$$



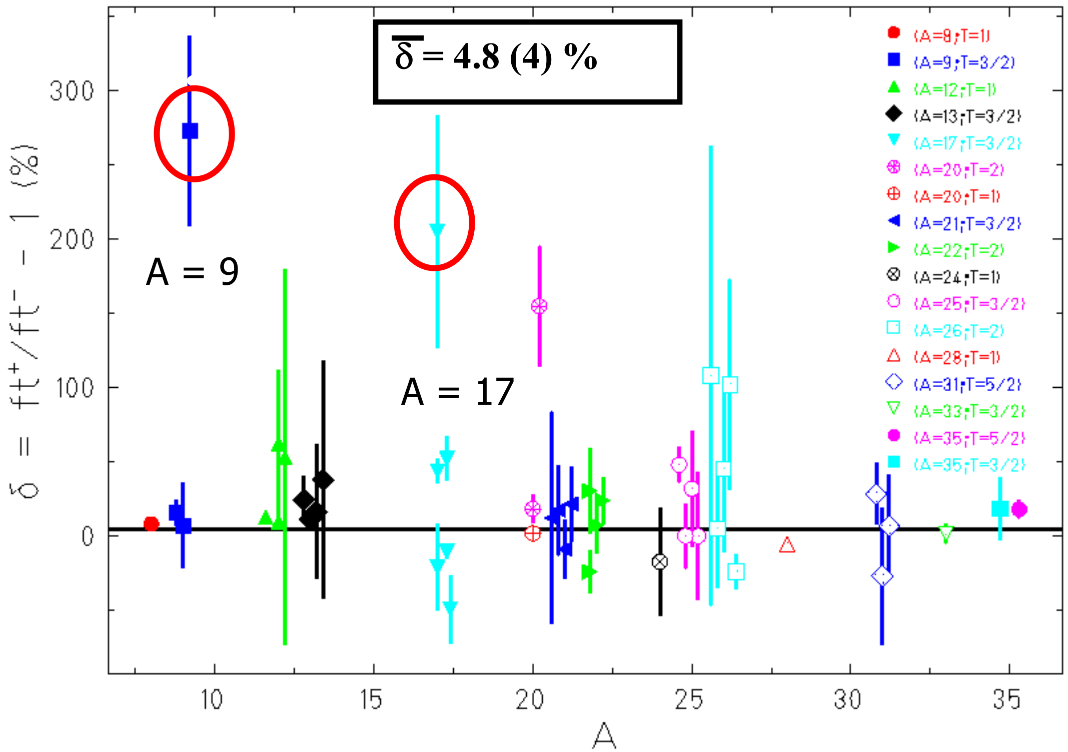
- Isospin symmetry breaking $\Rightarrow$ asymmetry in mirror β-decays

$$\delta = \frac{ft^+}{ft^-} - 1$$

$$\delta = \delta_{nuc} + \delta_{SCC}$$

Systematics of experimental δ values (A≤40)

Thomas et al., AIP Conf. Proc 681, p. 235



➢ **Allowed Gamow-Teller transitions (log(ft)<6)**

→**17 couples of nuclei**

→**46 mirror transitions**

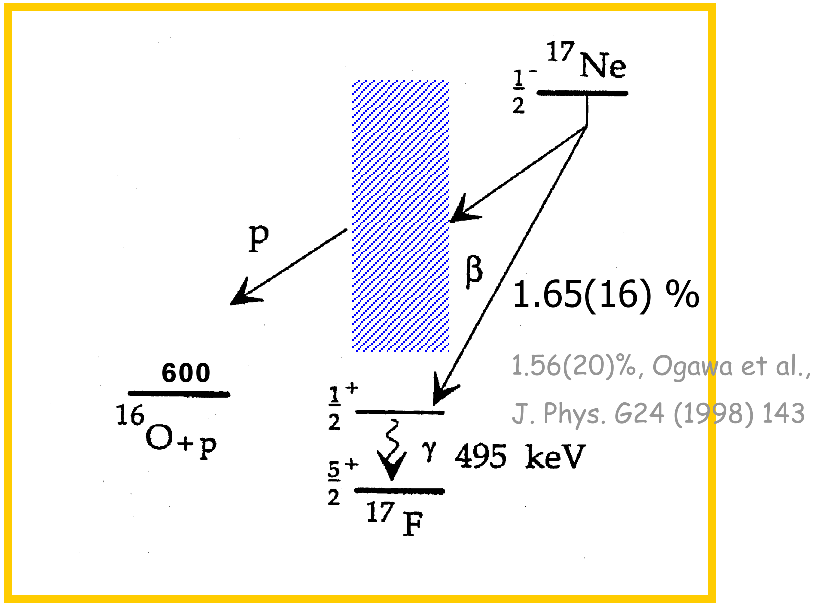
Average asymmetry δ :

11 (1) % in the 1p shell (A<17)

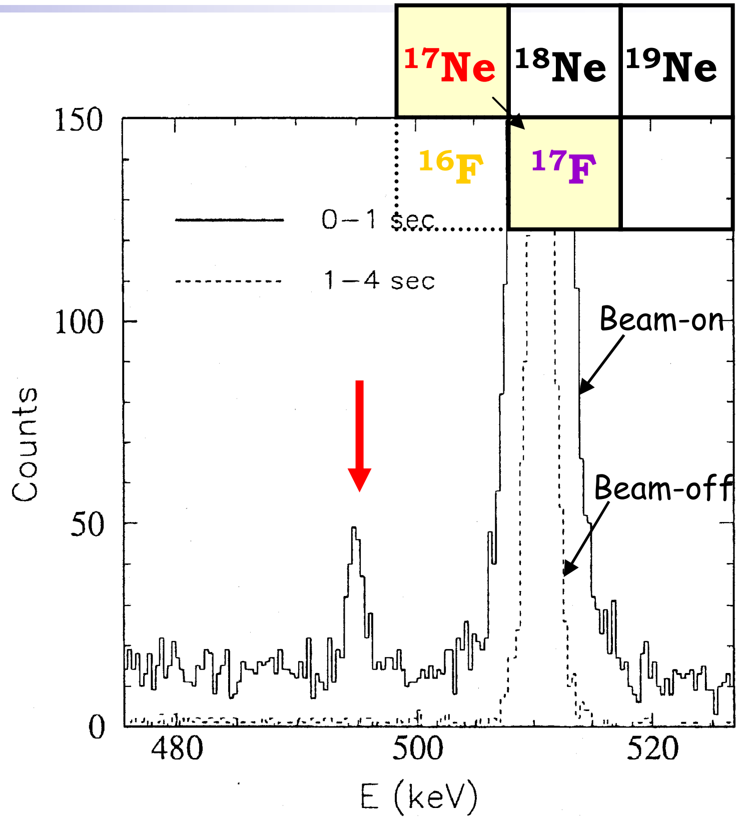
0 (1) % in the (2s,1d) shell (17<A<40)

First identification of a proton-halo state

Rolfs, NPA217(73)29



$$\delta = ft^{+}/ft^{-} - 1 = -0.55(09)$$



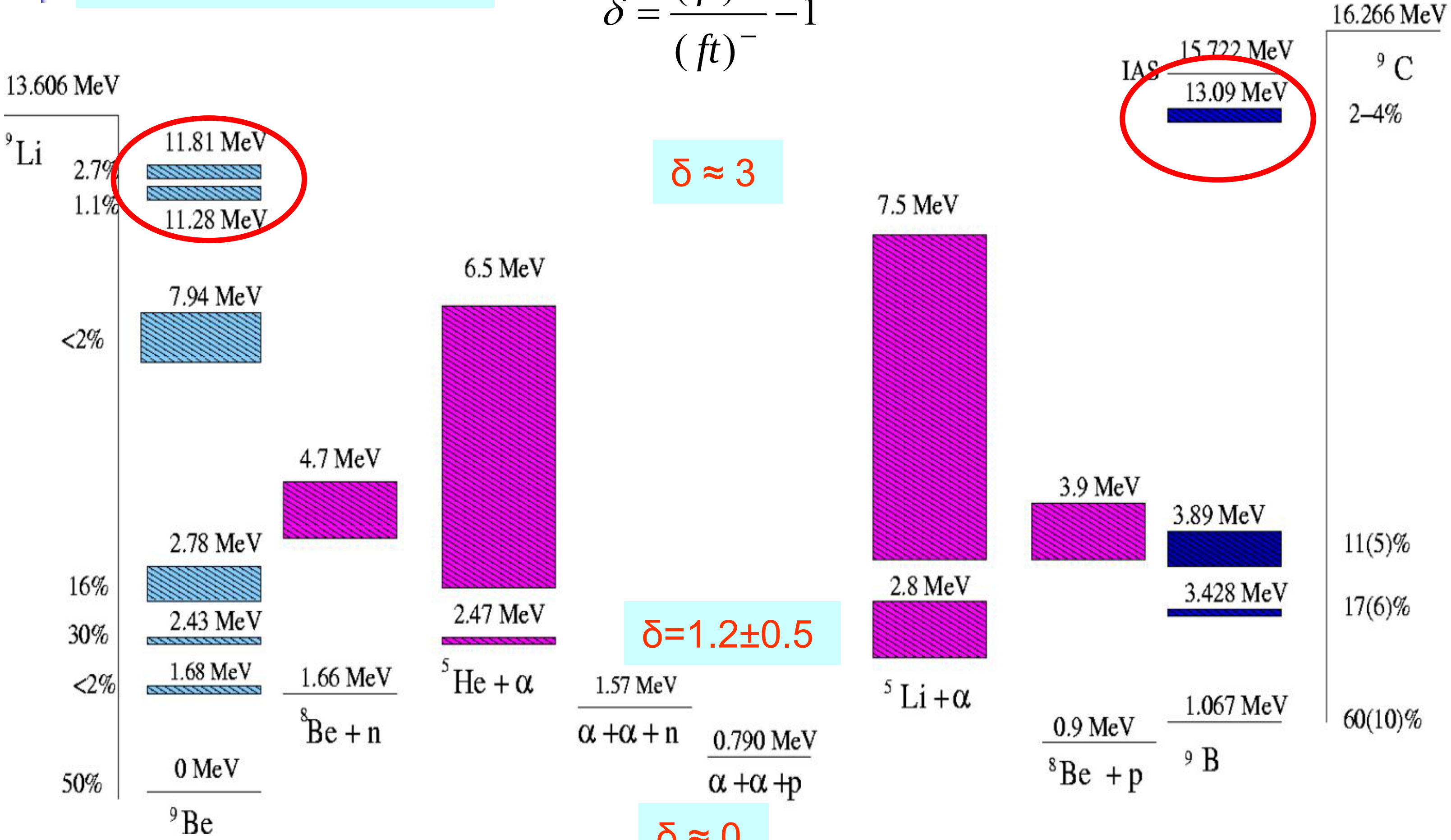
Borge et al., PLB317(93)25

Asymmetry ⟷ Halo Structure

A = 9 Isobar

Large asymmetries

$$\delta = \frac{(ft)^{+}}{(ft)^{-}} - 1$$



Nyman et al., NPA 510 (1990) 189 *Mikolas et al., PRC 37 (1988) 766*

F. Ajzenberg-Selove, NPA 490 (1988) 1

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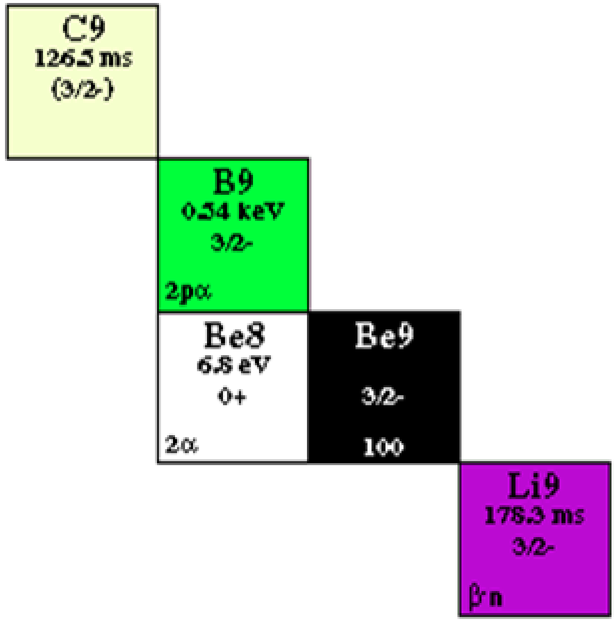
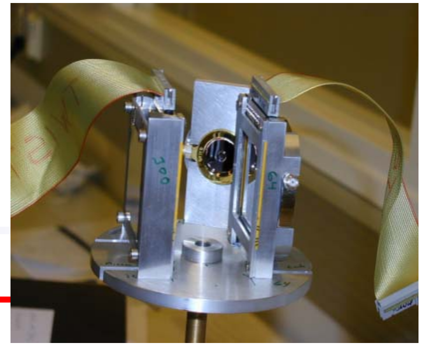
Why to Study Light Nuclei ?

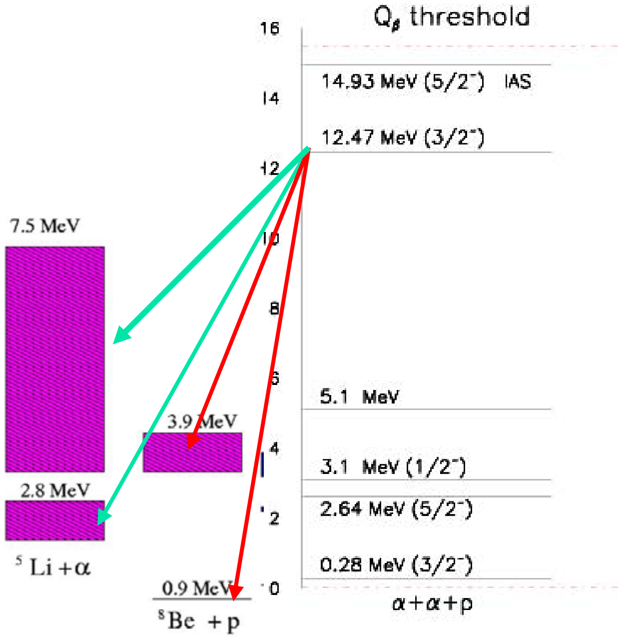
- "Exact" A-body calculations possible for $A \leq 12$
  - Green Funtion Monte-Carlo methods
  - Non-core Shell-model
- Crucial for bridging A=5 and A=8 gaps in
  - Big Bang and Stellar nuclear synthesis
    - The $\alpha(\alpha n,\gamma)^9Be$ + $^9Be(\alpha,n)^{12}C$
  - Competes with triple-α in n-rich scenarios
    - Importance of the $\alpha + n \leftrightarrow {}^5He(\alpha, \gamma)^9Be$
- Experimentally β-decay provides
  - Clean way to feed unbound states
  - Break-up mechanism not fixed by kinematics

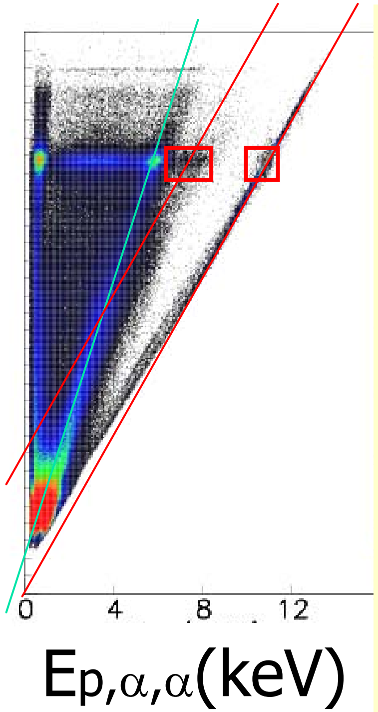


^{9}B States fed in β-decay of ^{9}C



$$E_{sum} = \frac{M_{recoiling} + M_{first}}{M_{recoiling}} E_{first} + x \begin{cases} = 92 \text{ keV } (9/8) \text{ for } ^8Be(0^+) \\ \approx 2 \text{ MeV } (9/5) \text{ for } ^5Li(3/2^-) \\ = 3.0 \text{ MeV } (9/8) \text{ for } ^8Be(2^+) \end{cases}$$





- Sequential Decay of 12.2 MeV State via ^{8}Be(gs), ^{8}Be(2$^+$), ^{5}Li(gs) and ^{5}Li(1/2)
- R-Matrix-formalism applied.
- MC-simulations to account for efficiencies of each channel
- Results E: 12.19(4) MeV

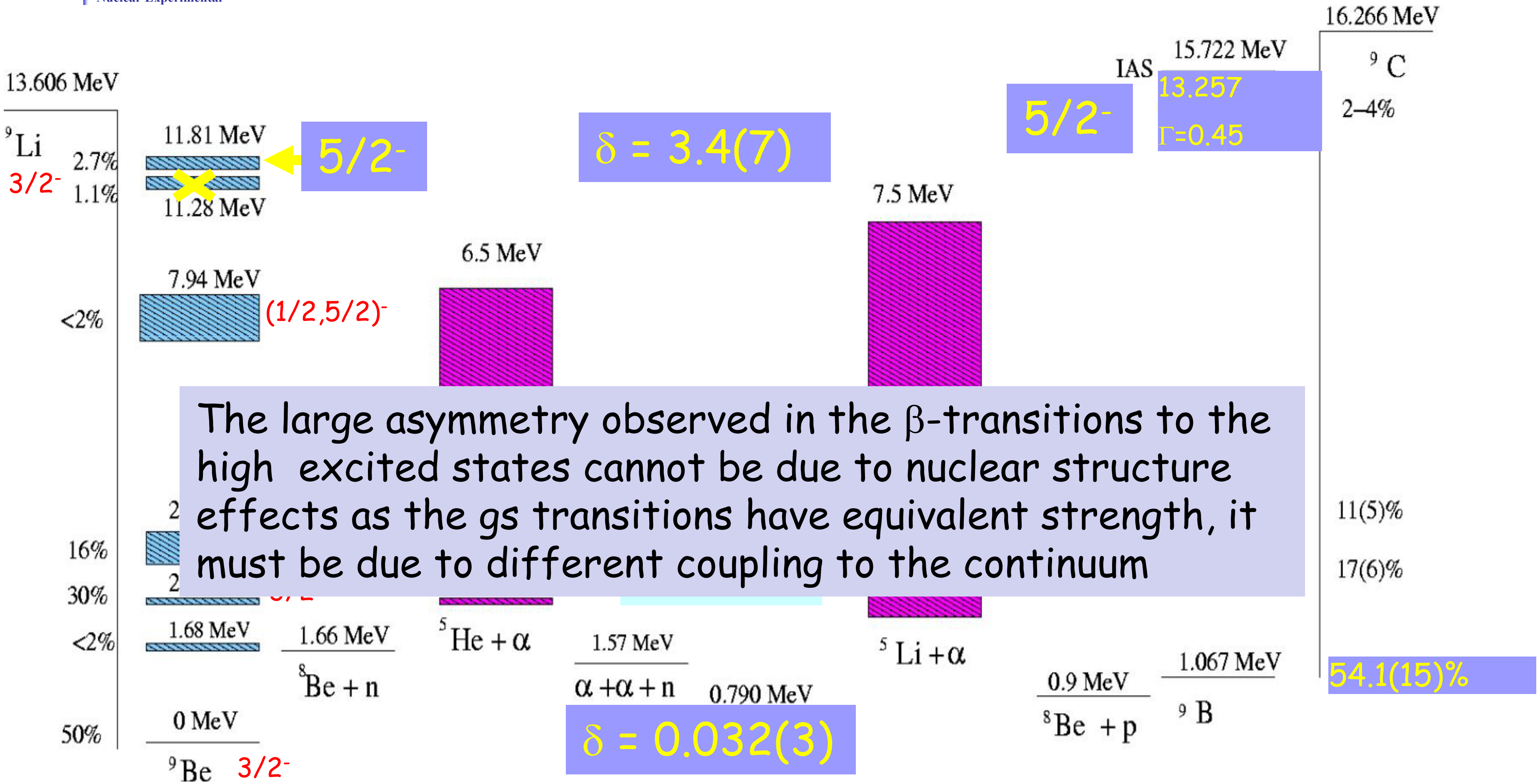
  Γ: 450(20) keV

  J: 5/2

  B_{GT}: 1.20(15)

UC Bergmann, NPA 692 (2001)427

A = 9 isobar



The large asymmetry observed in the β-transitions to the high excited states cannot be due to nuclear structure effects as the gs transitions have equivalent strength, it must be due to different coupling to the continuum

Nyman et al., NPA 510 (1990) 189

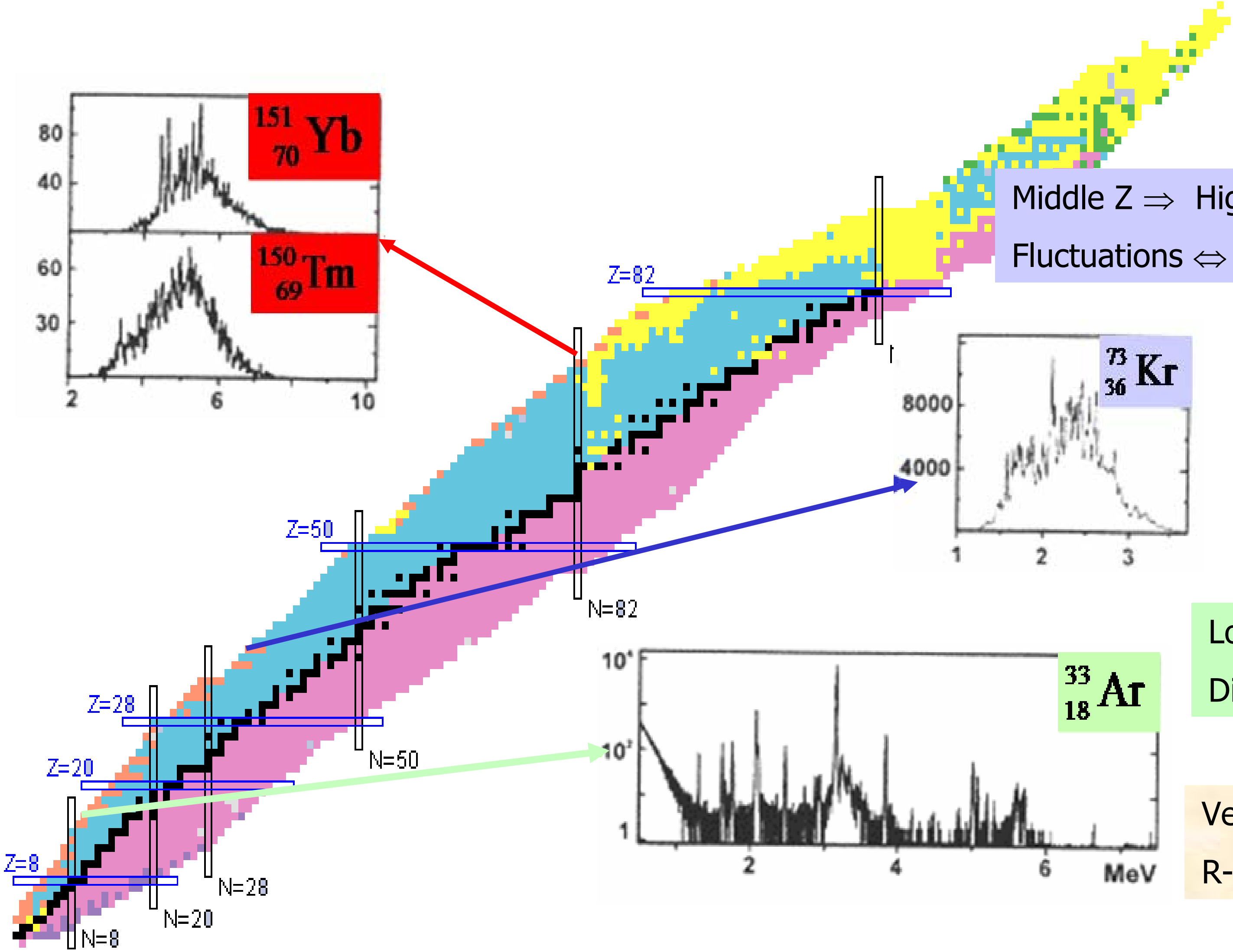
Mikolas et al., PRC 37 (1988) 766

PLB576 (2003)55

F. Ajzenberg-Selove, NPA 490 (1988) 1

NP A692(2001)427

Transition from order to Chaos



Middle Z ⇒ High Density Narrow States

Fluctuations ⇔ Porter Thomas Distribution

Low Z ⇒ Narrow States

Direct structure information

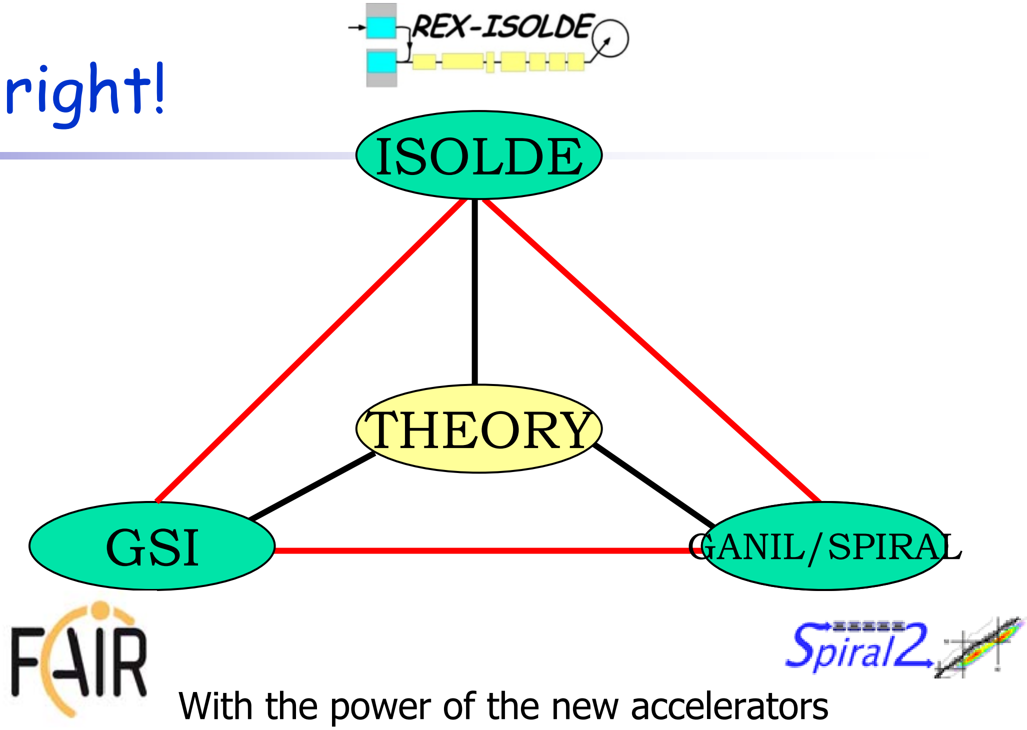
Very low Z ⇒ Broad States

R-Matrix description: E, Γ

Summary

- Decay modes: peering into nuclear structure
- Exotics decays: testing shell model beyond the drip line
  peering into nucleon-nucleon correlations
- Large Asymmetries: ^{17}Ne, ^{17}N halo structure
  ^{9}C, ^{9}Li coupling to the continuum
- Level densities → Fluctuations → Chaos
  ↓
  Relevant for astrophysics

The future is bright!



With the power of the new accelerators

And the developments in detectors

We will discover new structures and

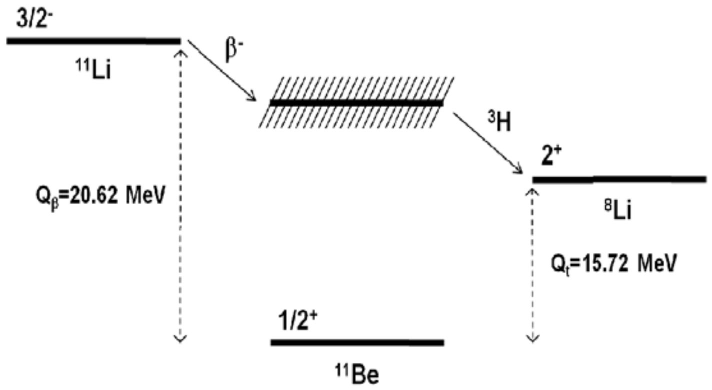
characterize the inmense amount of

new nuclei

Thanks

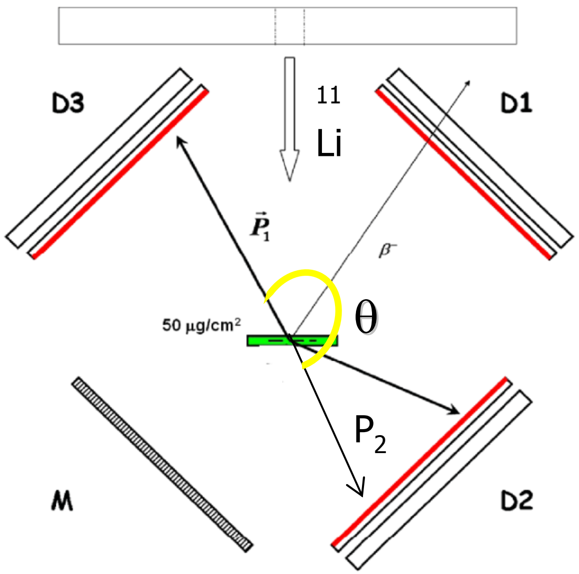
for your Attention!!

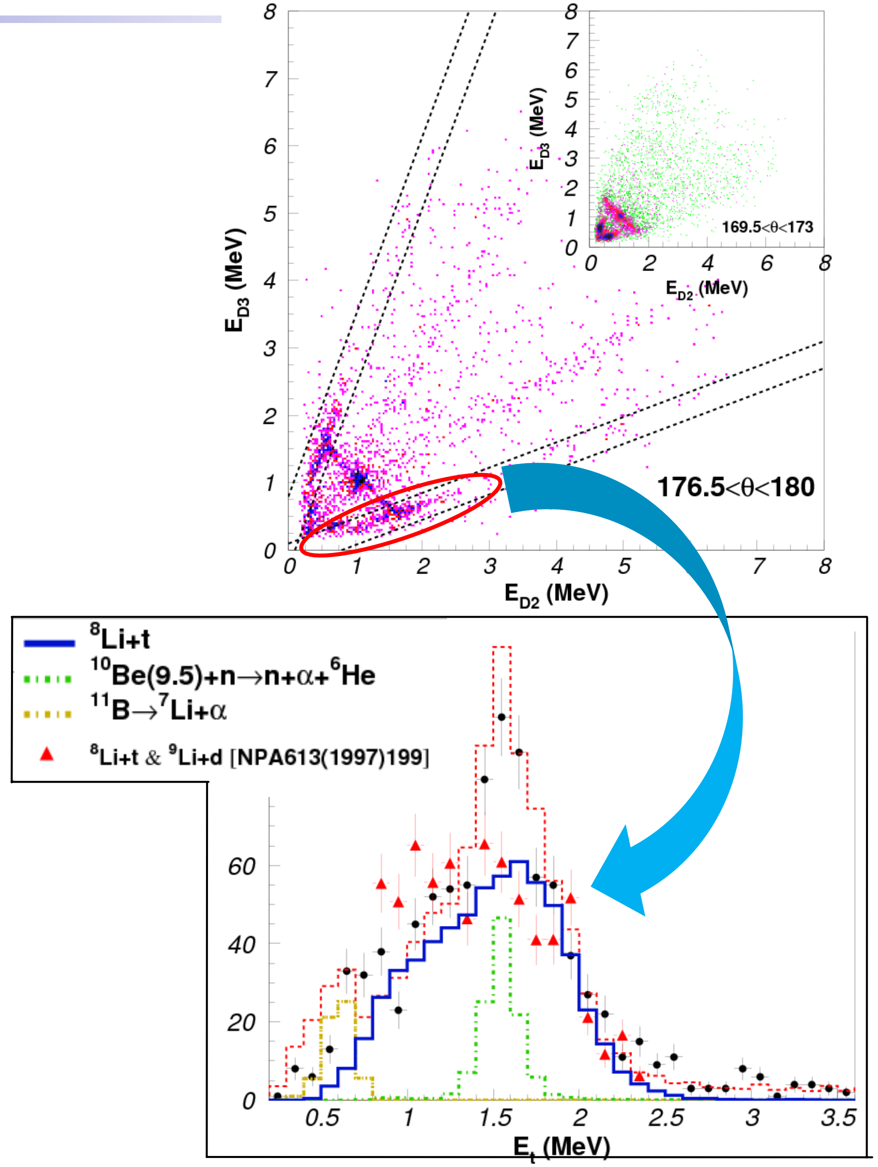
Kinematic identification of βt emission in ^{11}Li



$Q_{\beta t} = \Delta M(^{11}Li) - \Delta M(^{8}Li) - \Delta M(t) = 4822(5)$ keV

PRL 100 (2008) 182501





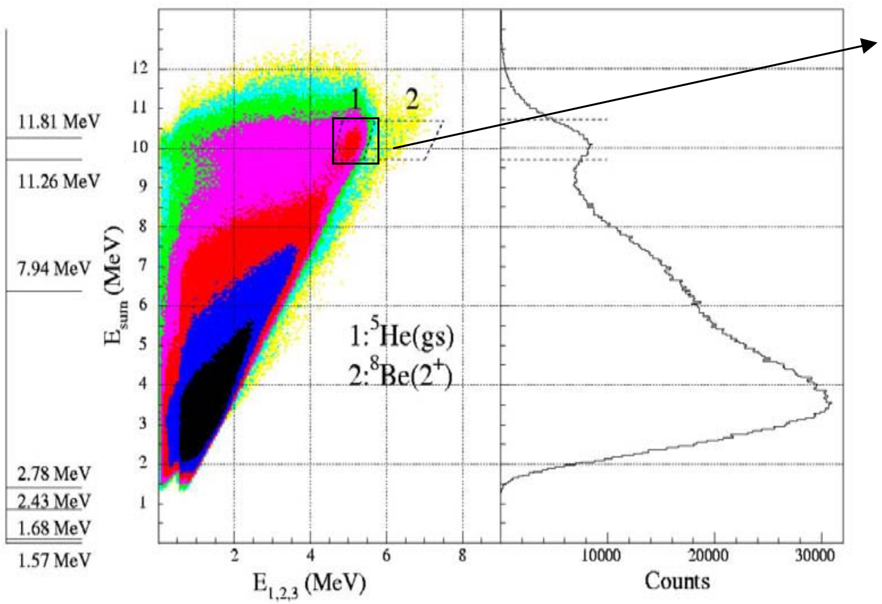
Beta feeding to the 11-12 MeV region in ^{9}Be

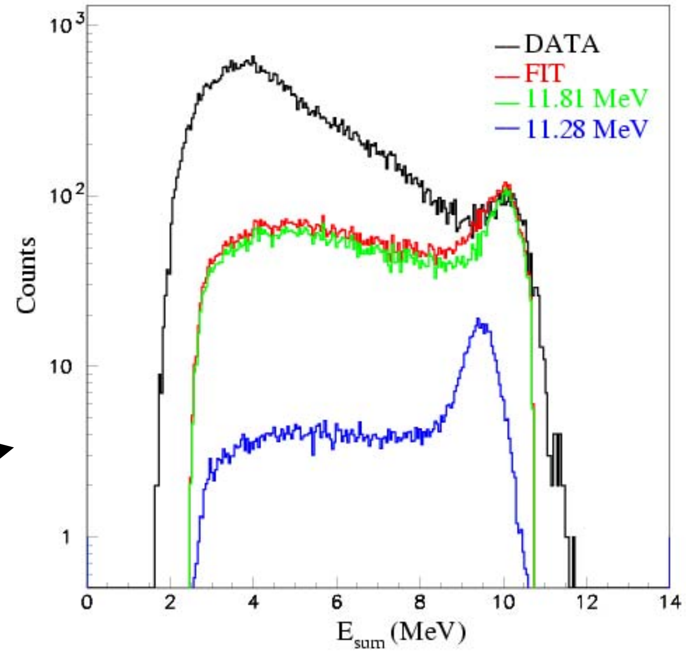
Fit of the high energy peak gating on the $^{5}He(3/2^{-})$ channel

11.81 MeV state → 91±10%

11.28 MeV state → 9 %

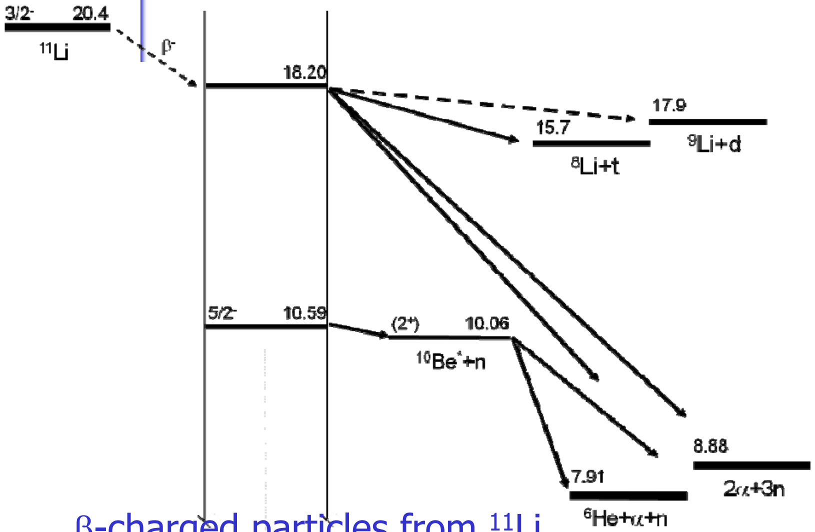
(e,p)-scattering on ^{9}Be assumed J = 7/2



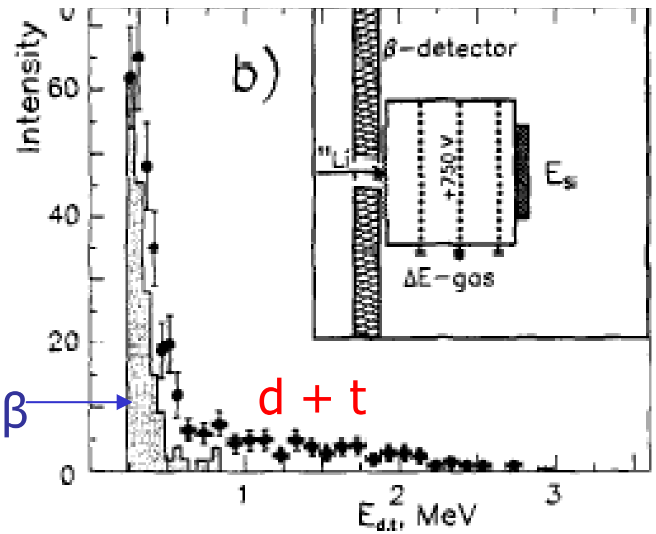


Only the participation of the 11.81 MeV state in ^{9}Be for the beta feeding is considered

^{11}Li (βd) @ ISOLDE



β-charged particles from ^{11}Li



✓ Complicated decay

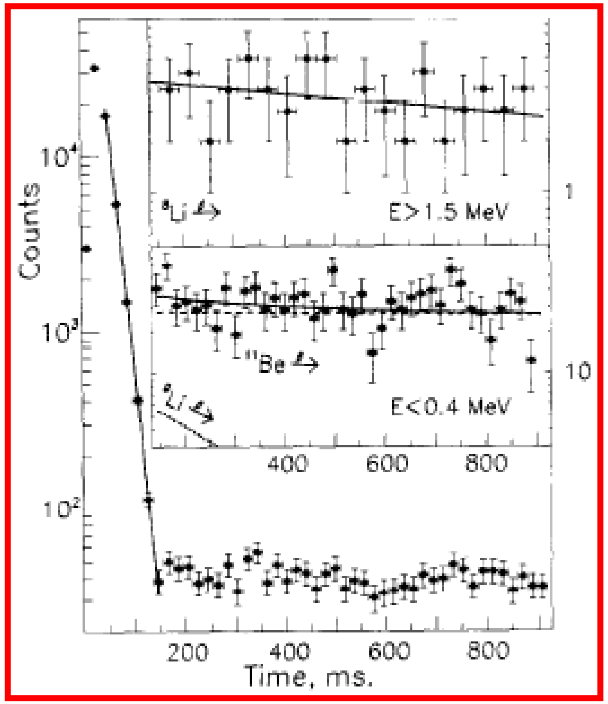
✓B.R. of βd ~ βt

✓ Used of pulsed structure of ISOLDE beam

Identification of the βd branch by energy and time correlation

Study of correlation between the Z = 1 particles (T < 0.06 ms) and delayed alphas between 0.15 < T < 0.9 s

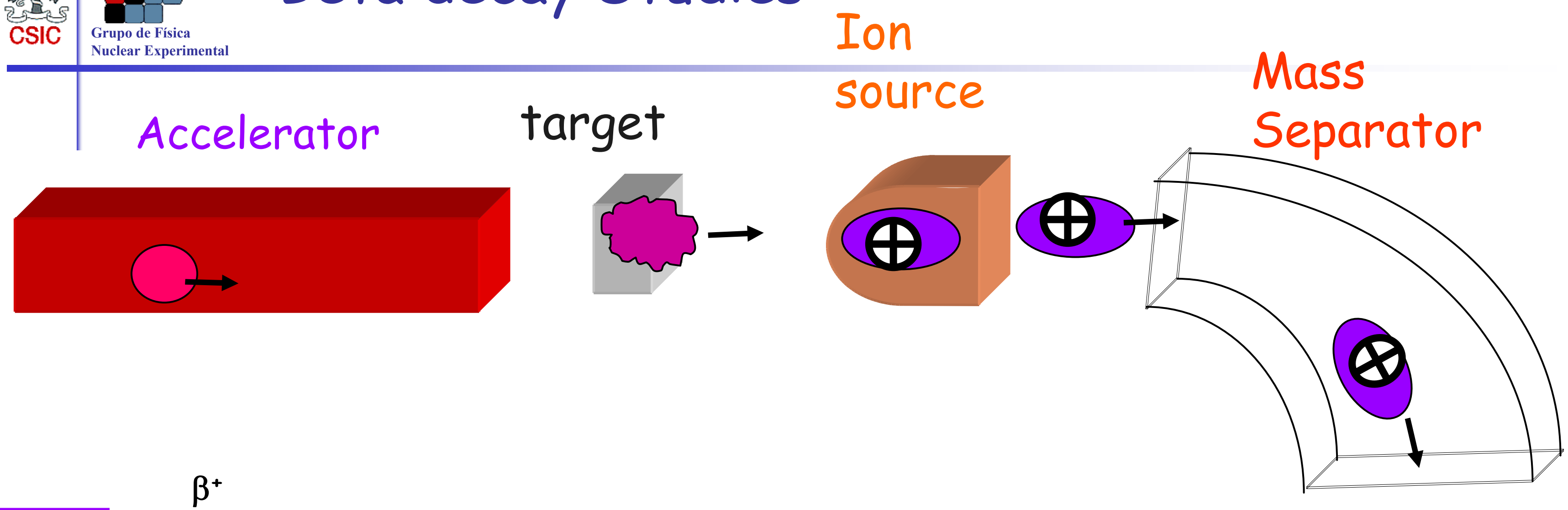
Time correlation

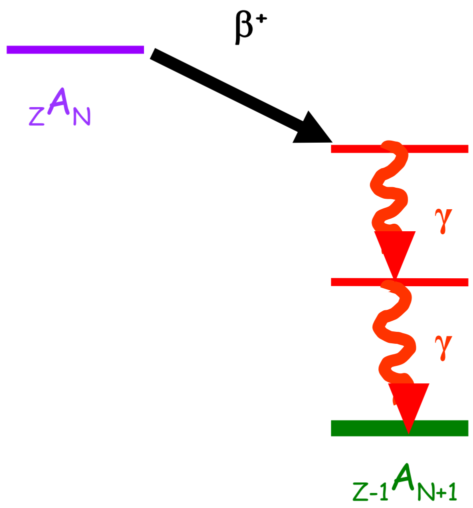


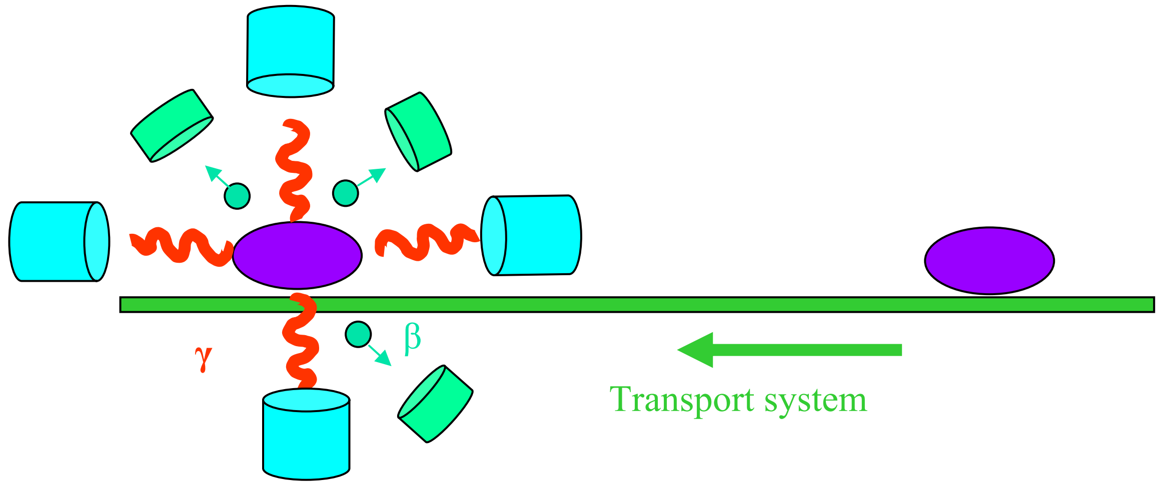
B.R.(βd) ~ 1x10^{-4}

PLB367 (96) 65

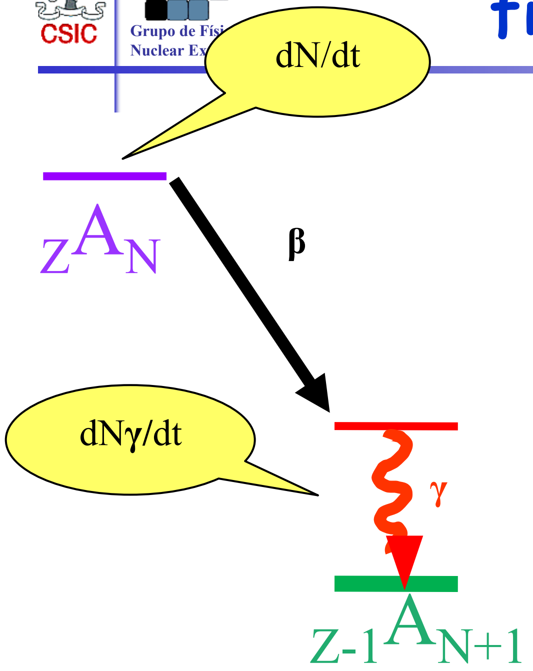
Beta decay Studies





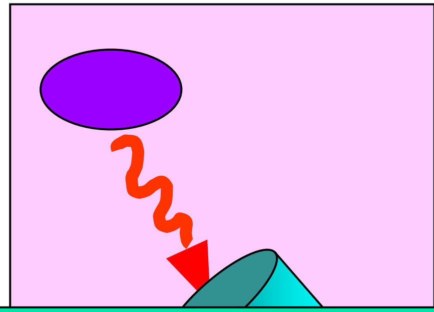


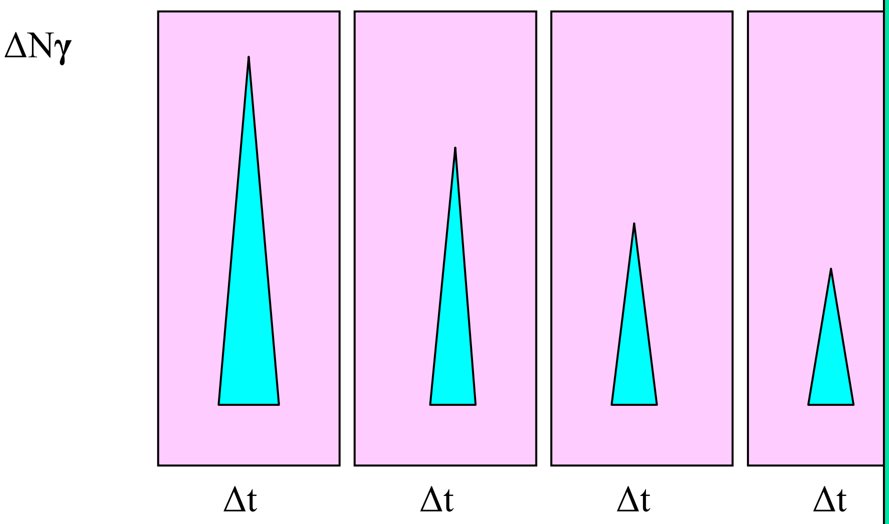
Half life measurement, first glance into nuclear structure

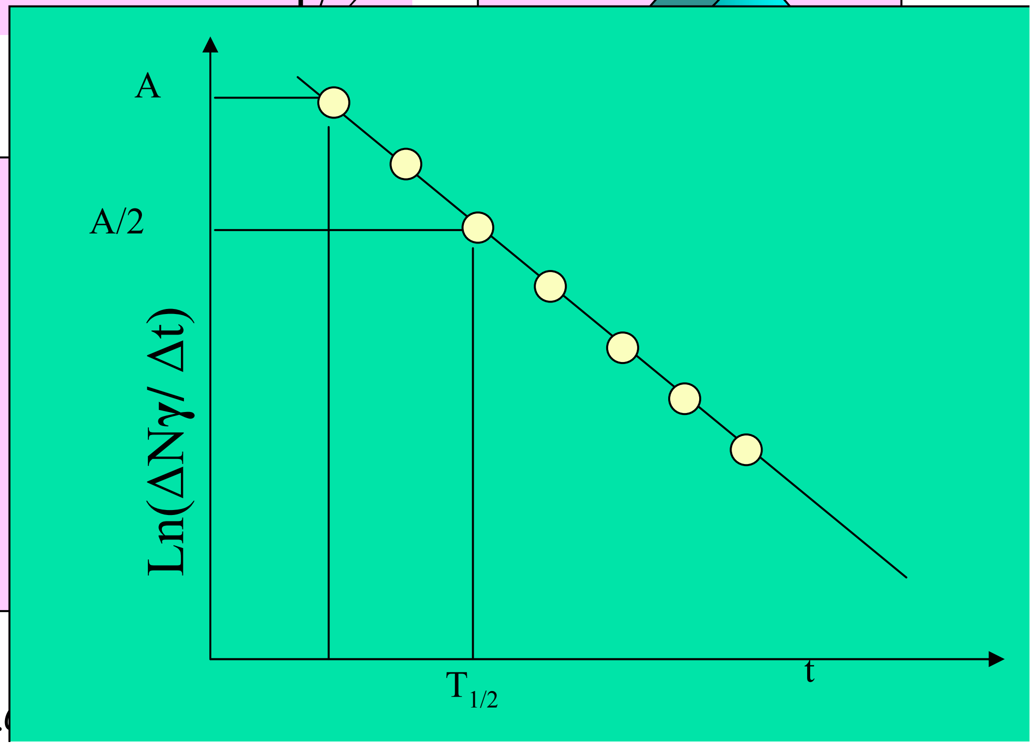


$$\frac{dN}{dt} = \frac{dN_0}{dt} e^{-\lambda t}$$

$$\lambda = \frac{1}{\tau} = \frac{Ln2}{T_{1/2}}$$







In the 90´s explosion of information on proton radioactivity ⇔ 28 emitters from gs

- Known proton emitters
- Proton emitting from isomers and g.s.
- Fine structure in proton emitters

82

50

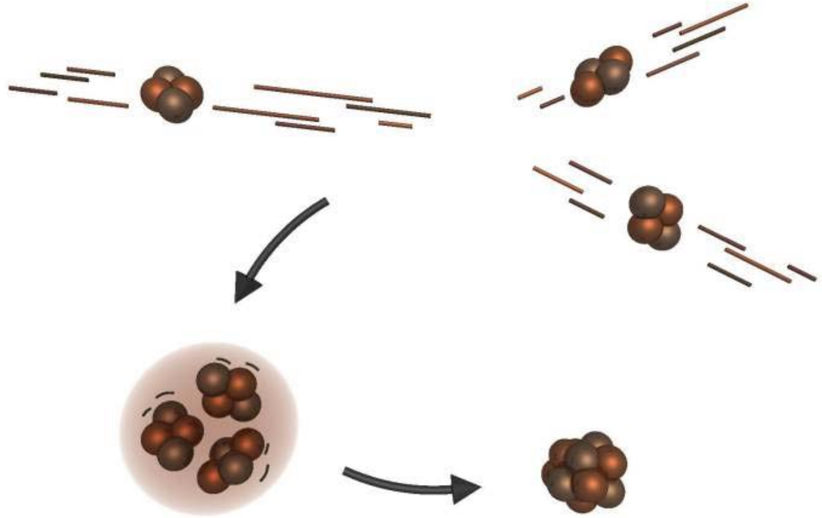
- *Theoretical models* are able to reproduce the systematic of p-decay spectroscopic factors for a wide range of spherical nuclei ⇒ sensitive test of Shell Model at the edge of stability
- p-emission from *highly deformed* nuclei has been observed and decay rates explained assuming Nilsson states
- No proton emitter observed in Z = 61.
- Proton emission from isomeric states observed for nuclei with Z < 50: ^{53m}Co; ^{58m}Cu; ^{94m}Ag;

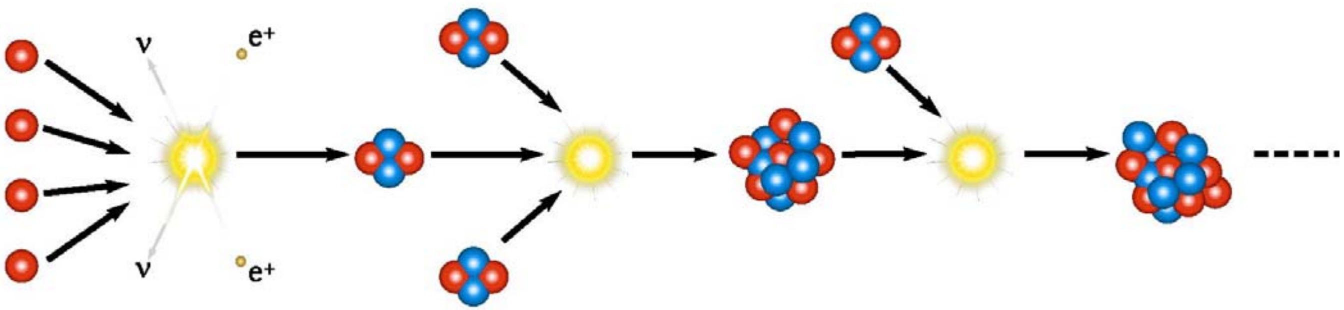
Tripple-alpha process

He-burning in stars proceeds

via the unbound nucleus ^{8}Be

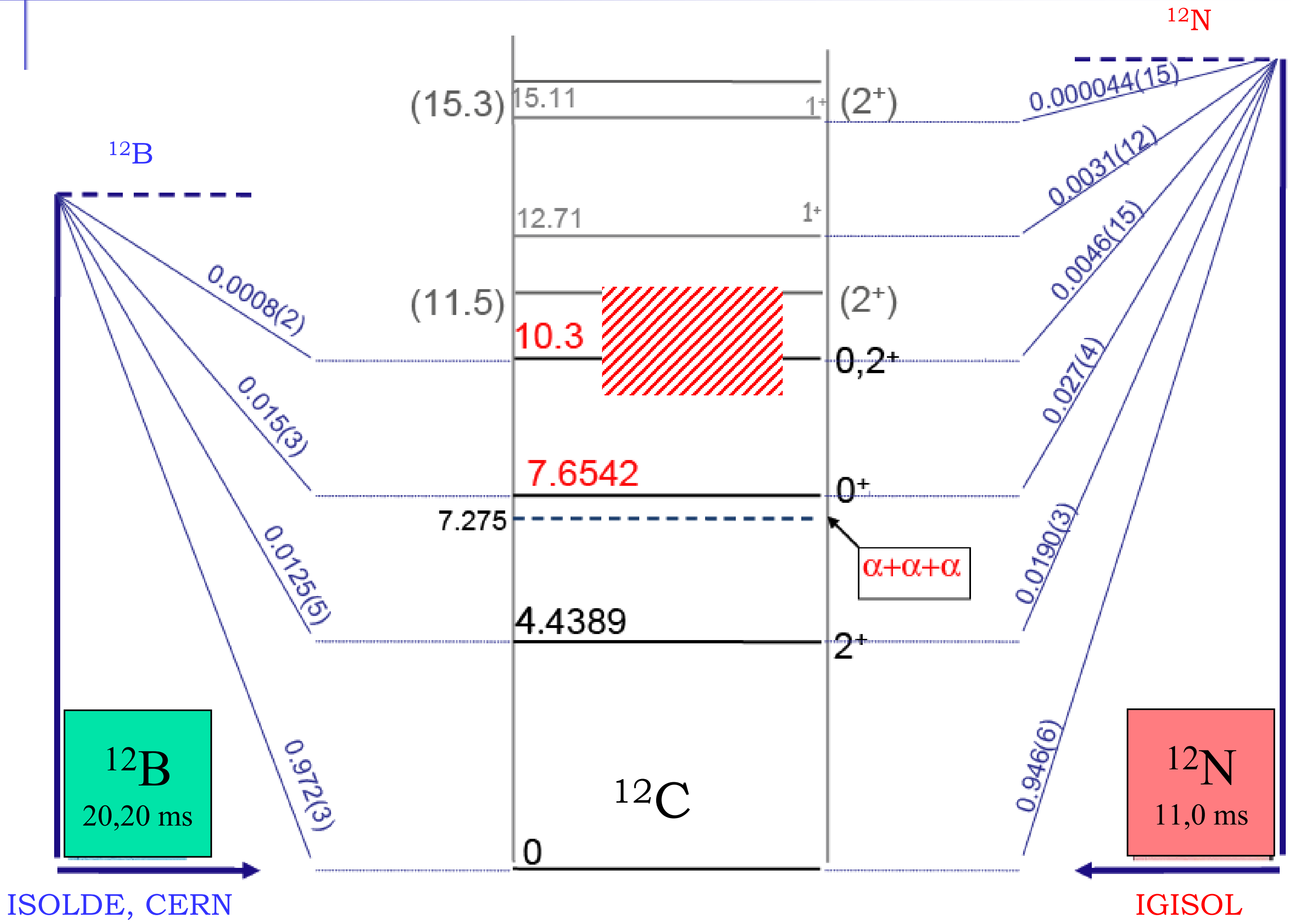
and the "Hoyle state" in ^{12}C



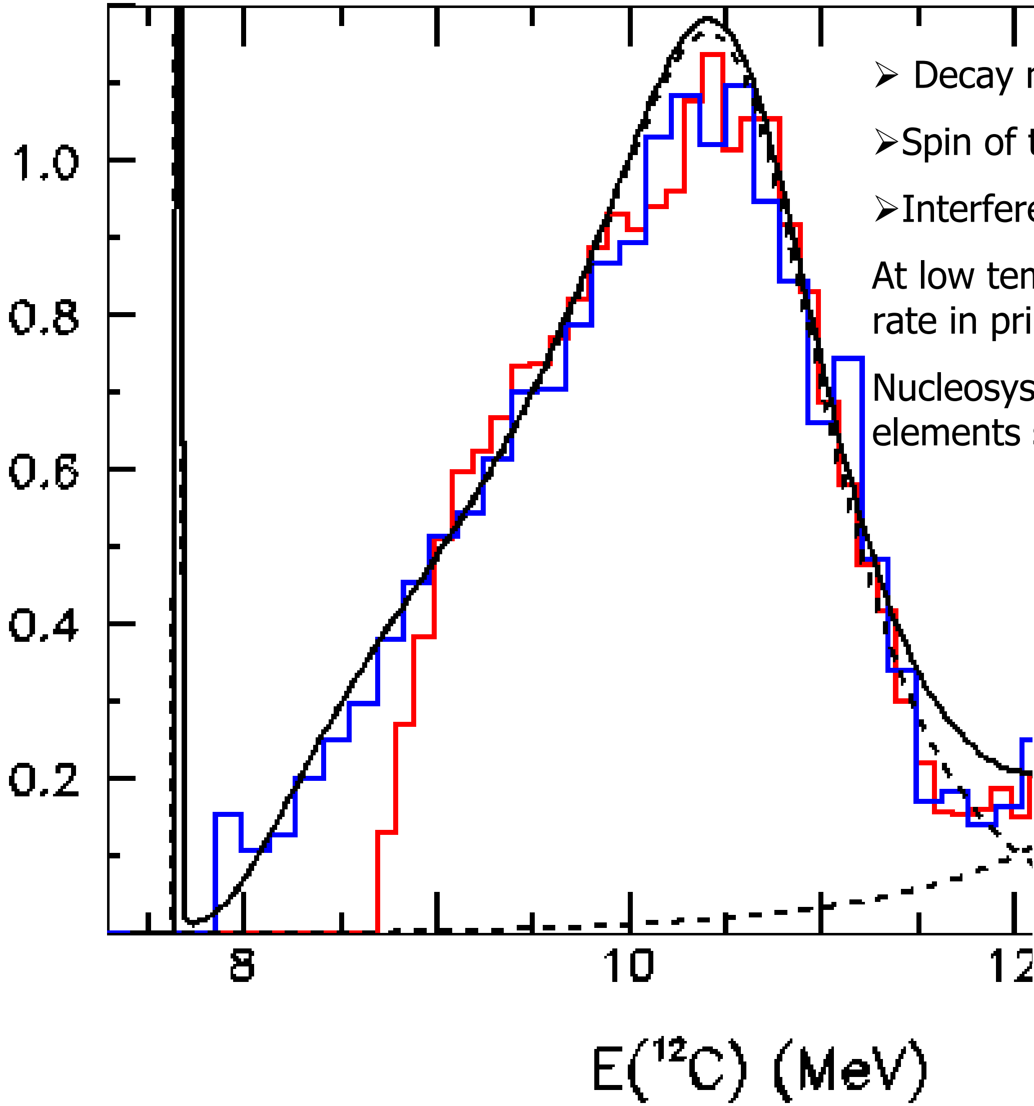


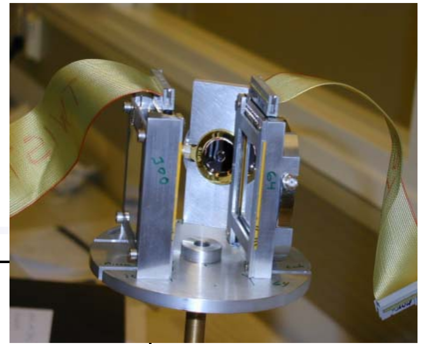
$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He \qquad 3\,{}^{4}_{2}He \longrightarrow {}^{12}_{6}C \qquad {}^{12}_{6}C + {}^{4}_{2}He \longrightarrow {}^{16}_{8}O$

^{12}C from the β-decays of ^{12}N and ^{12}B



Combined fit of ^{12}B and ^{12}N

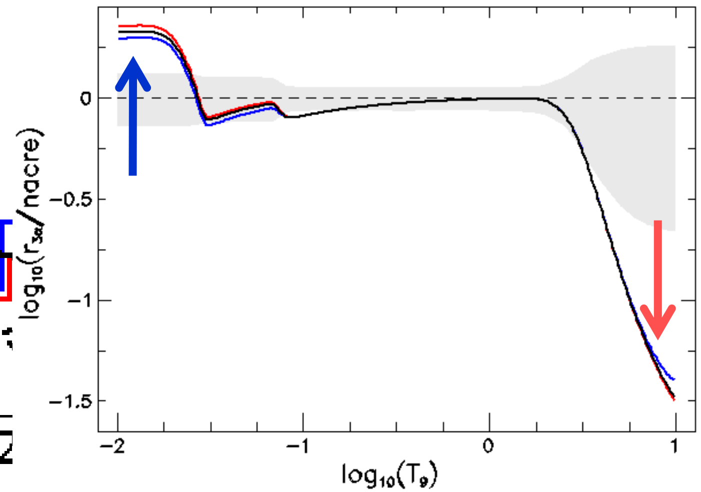




- Decay mode identified
- Spin of the 10 MeV 0+
- Interferences with Hoyle state

At low temperature fusion of 3α-rate in primordial stars faster

Nucleosysntesis of heavy elements slower



Nuclear Astrophysics Compilation of REaction Rates,

C. Angulo et al.., NPA 656 (1999) 3

Stringent test of Nuclear Models

CSIC
Grupo de Física Nuclear Experimental

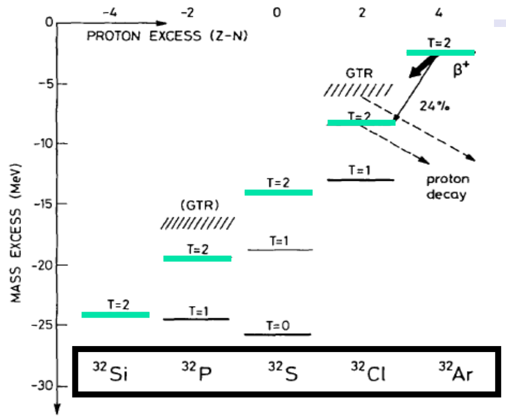
✓Test Isobaric Multiplet Mass eq.

$M(A,T,T_z) = a + bT_z + cT_z^2 + \delta(dT_z^3 + eT_z^4)$

✓ If 2-body forces responsible of charge dependence in nuclei IMME to T_z^2

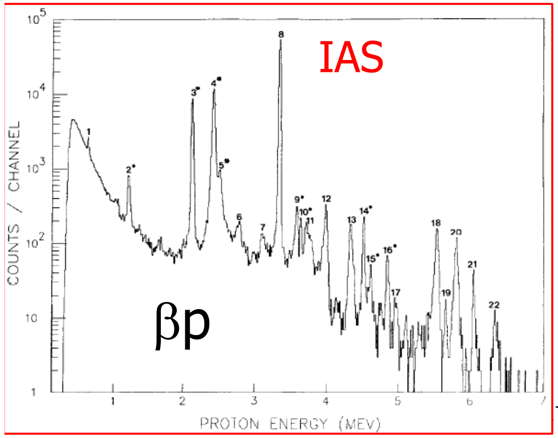
✓ $B_F = T(T+1) - T_{Zi}T_{Zf}$

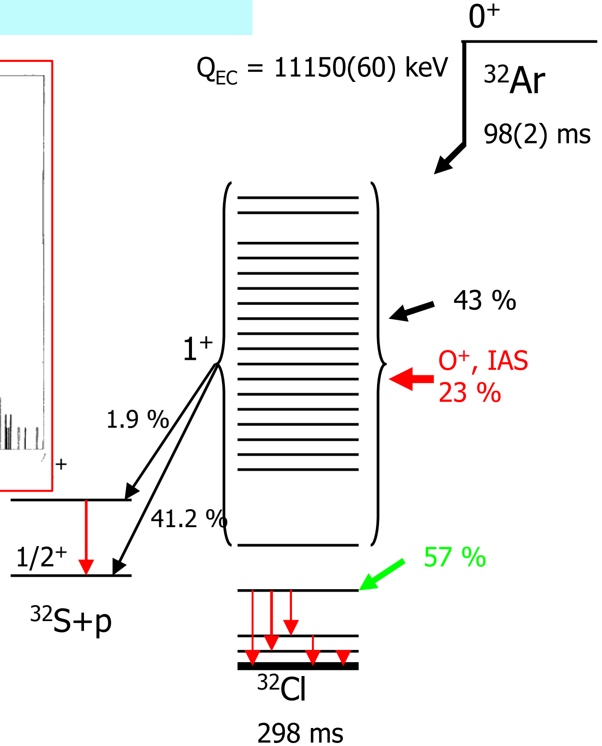
✓ If strength to IAS $\neq B_F \Leftrightarrow$ Isospin Mixing

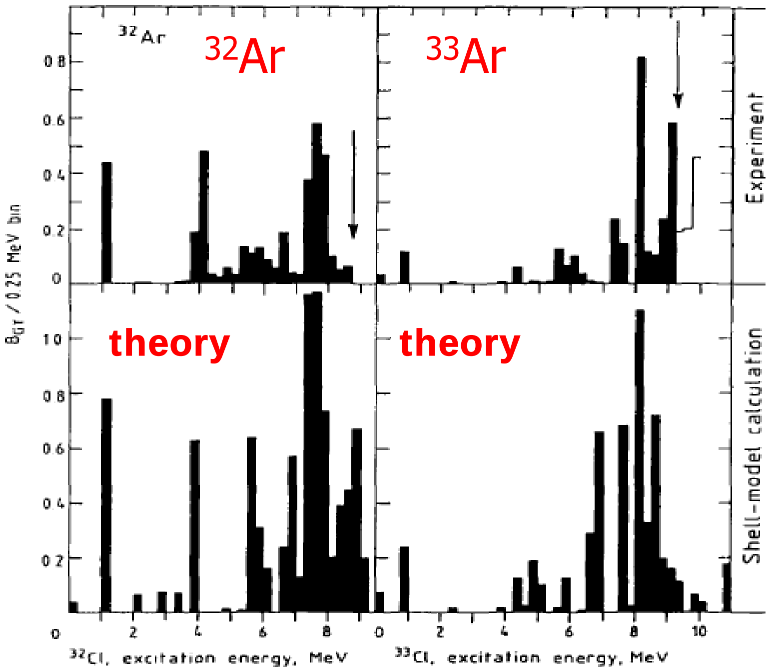


✓ Impressive reproduction of the B_{GT} distribution by Shell Model calculation

✓ Quenching factor close to one, sensitive to the placement of the GTGR

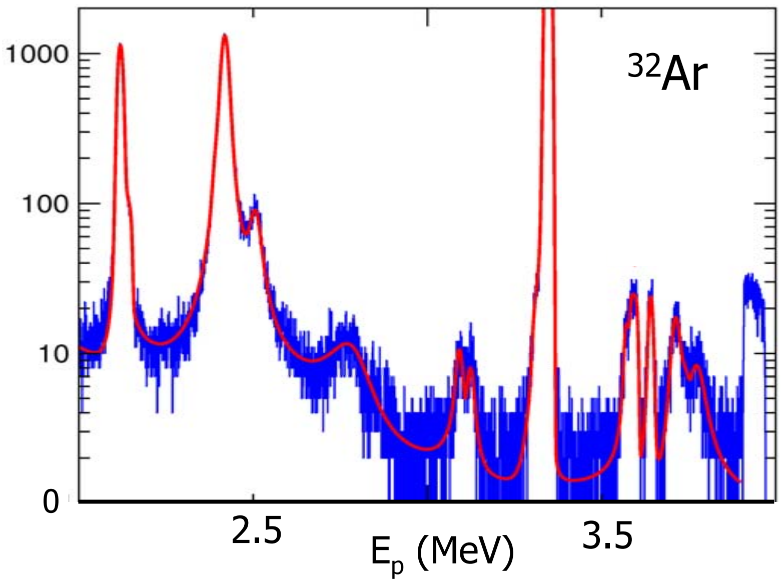


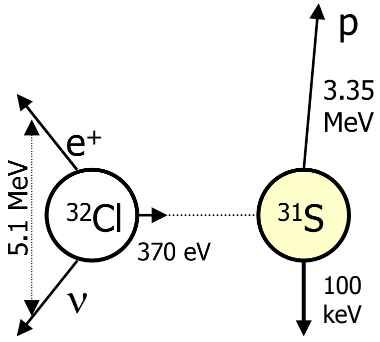




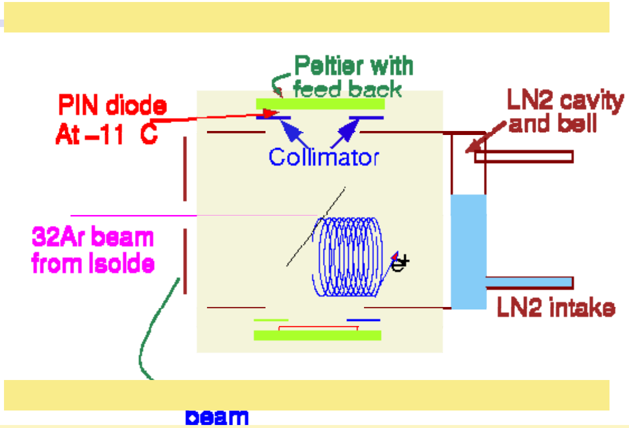
Björnstad et al, NPA443 (85) 283

Search for New Physics



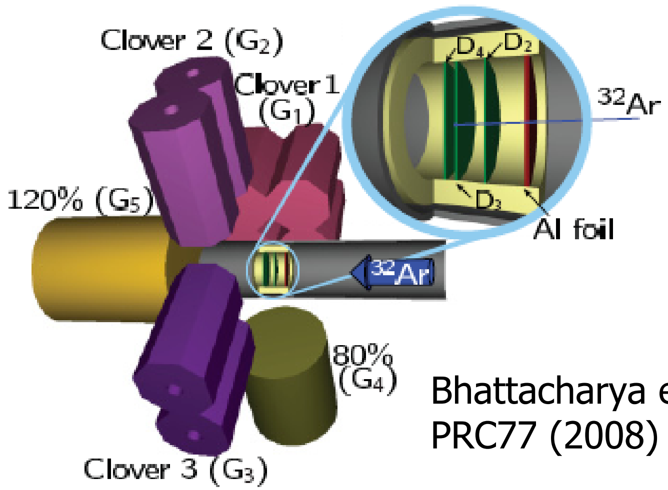


- Set-up to avoid β-summing @ ISOLDE



The V-A character of β-decay determined by measuring e-ν correlation [Johson,PR132(63)]

- If βp emitter ⇒ measurement of e-ν correlation from the broadening of proton peak from IAS
- Isospin mixing in Fermi decays
- Limit for scalar component in beta decays



Bhattacharya et al., PRC77 (2008) 065503

- Absolute branching ratios /MSU
- Very precise $T_{1/2}$ determination /ISOLDE
- ft = 1552(12) s for the Fermi decay
- Isospin Symmetry breaking Correction

δ_c = 2.0(4) %

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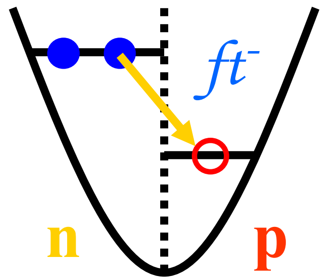
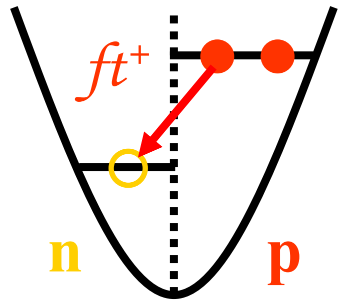
Mirror Asymmetry & Systematics

$\beta^+ \; : p \rightarrow n + e^+ + \nu$

$\beta^- : n \rightarrow p + e^- + \bar{\nu}$

$\text{E.C.} : p + e^- \rightarrow n + \nu$





$$\delta = \frac{ft^+}{ft^-} - 1$$

$$\delta = \delta_{nuc} + \delta_{SCC}$$

Thomas et al., AIP Conf. Proc 681, p. 235

➢ **Allowed Gamow-Teller transitions (log(ft)<6)**

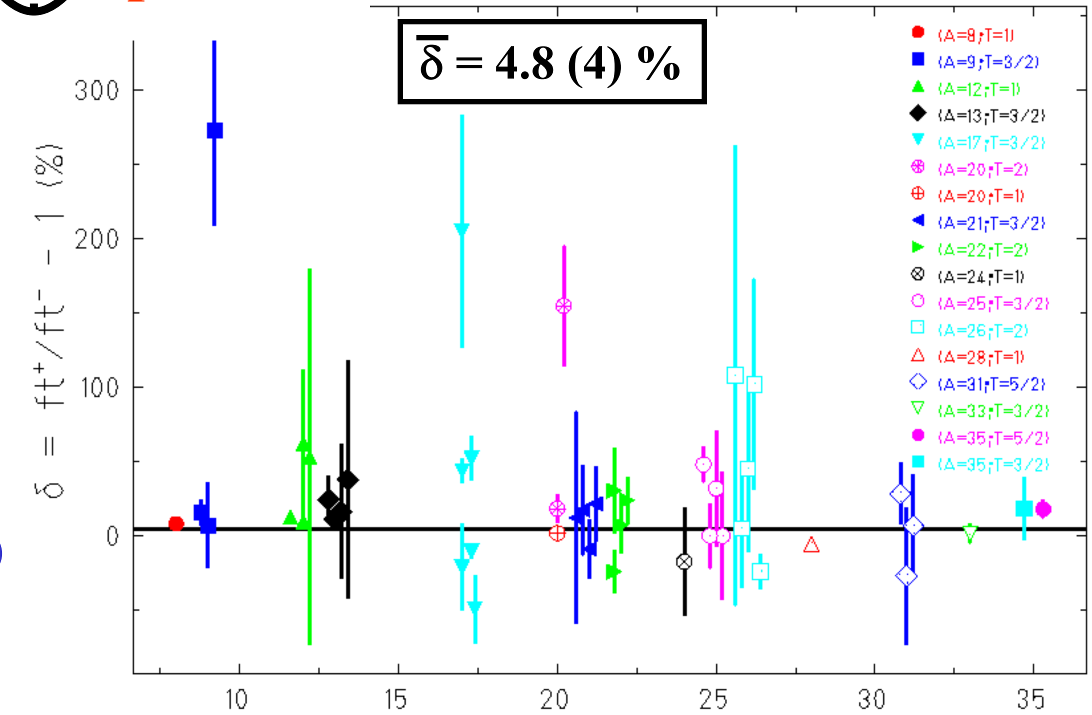
→**17 couples of nuclei**

→**46 mirror transitions**

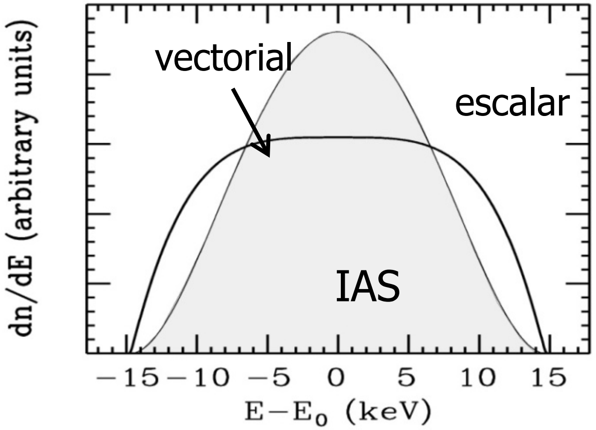
Average asymmetry δ :

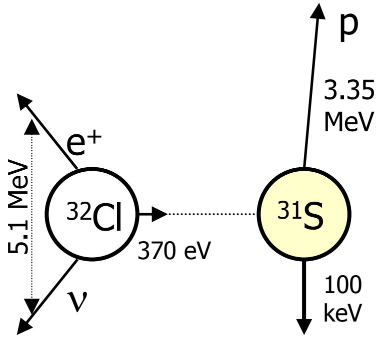
11 (1) % in the 1p shell (A<17)

0 (1) % in the (2s,1d) shell (17<A<40)

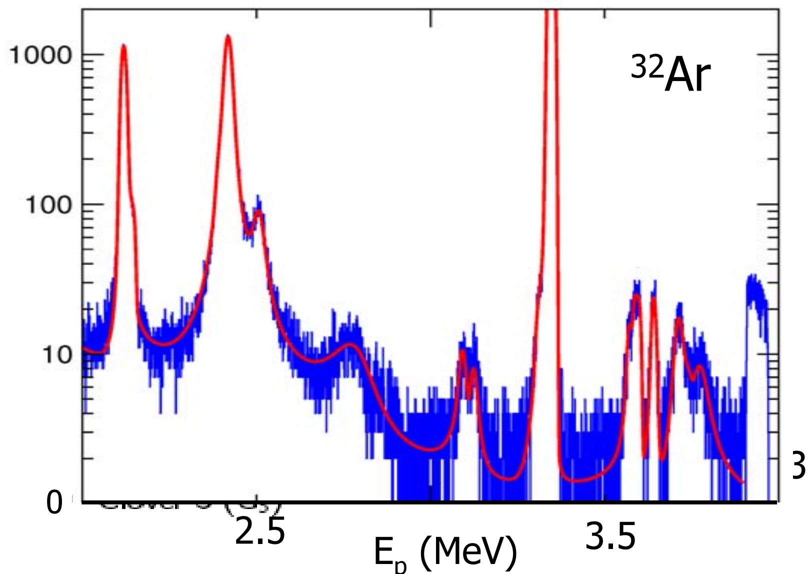


Search for New Physics

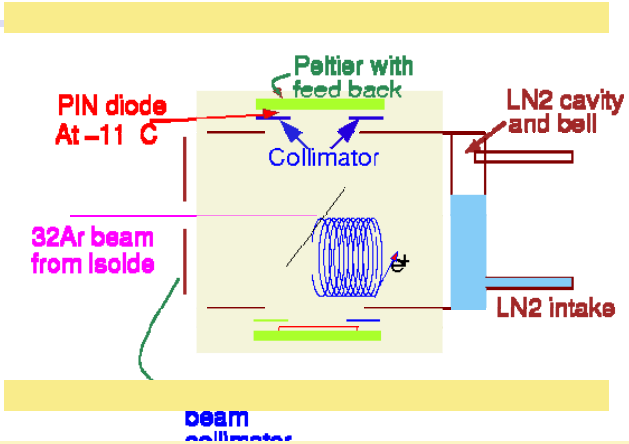




If βp emitter ⇒ e-ν correlation determined from the broadening of proton peak from IAS



- Set-up to avoid β-summing @ ISOLDE



e-ν correlation a good probe of weak interactions

The V-A character of β-decay determined by measuring e-ν correlation in 1963

- Isospin mixing in Fermi decays
- Limit for scalar component in beta decays

- Absolute branching ratios /MSU
- Very precise $T_{1/2}$ determination /ISOLDE
- ft = 1552(12) s for the Fermi decay
- Isospin Symmetry breaking Correction

δ_c = 2.0(4) %